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STUDY ON HULL CORROSION AND COATINGS

Prepared for
Transportation Development Centre
Policy and Coordination Group
Transport Canada TP 9493E

by

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Un sommaire en français de ce rapport est inclus avant la Table des matières.

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17. Abstract

A state-of-the-art report on methods used to control external hull corrosion on ice-going vessels has been prepared. Information was obtained by literature search; field trips to eastern Canada, Finland and England; and by contact with companies operating such vessels in the Canadian Arctic. The primary findings are:

1. Weld and weld zone corrosion can be controlled by using noble weld consumables and by controlling heat inputs to the weld zone.

2. High-solids coatings (epoxies and polyurethanes) have been successfully used to reduce hull corrosion and friction. The key to their success lies in proper application conditions.

3. Impressed-current cathodic protection is effective in controlling hull corrosion, particularly when used with high-performance coatings. Such coatings and cathodic protection act synergistically in protecting ships hulls from corrosive attack.

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17. Résumé

Ce rapport rend compte du tour d'horizon qui a été fait des méthodes couramment utilisées pour protéger la coque des navires brise-glace contre la corrosion. Les renseignements ont été obtenus par voie de recherche documentaire, de voyages sur la côte Est du Canada, en Finlande et en Grande-Bretagne et de contacts auprès des armateurs exploitant des navires dans les eaux arctiques canadiennes. Les principales conclusions sont les suivantes:

1. Les cordons de soudure et les zones affectées thermiquement résistent mieux à la corrosion si on utilise des métaux d'apport plus nobles et par le réglage approprié des apports thermiques au soudage.

2. Les revêtements à forte teneur en solides (résides époxydiques et polyuréthannes) luttent avec succès contre la corrosion et réduisent le frottement, dans la mesure où leur application a été convenablement faite.

3. La protection cathodique par courant imposé permet d'enrayer la corrosion, surtout en association avec un revêtement haut rendement, produisant un effet de synergie qui accroît l'efficacité de la lutte contre la corrosion.

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SUMMARY OF REPORT

A. Objectives

This study was commissioned by the Transportation Development Centre (TDC) of Transport Canada to produce a state-of-the-art report on the methods used to control external corrosion on hulls of ice-going vessels. Since the causes of corrosion must be understood to properly apply control measures, it was necessary to examine all factors bearing on hull corrosion from weld metallurgy through coating application conditions to the science of cathodic protection. TDC intended that the study would provide a report which would serve as a reference text for ice-going vessel construction and operation and which would be amenable to expansion as new information became available.

B.H. Levelton and Associates Ltd. were aided in the study by Peter S. Hatfield Ltd., marine architects, who provided invaluable data on ship construction codes, methods of fabrication, and other matters relating to ice-going vessels specifically. B.H. Levelton and Associates Ltd. provided the expertise in welding technology, corrosion mechanisms, coating technology and cathodic protection, as well as compiling data and preparing the report.

B. Methodology

The accumulation of information proceeded in a series of tasks, most of which proceeded concurrently.

1. Assemble all data on ship construction codes including data from Peter S. Hatfield Ltd., shipyards, and Canadian and US navies.

2 Conduct a literature search to obtain all pertinent data on ice-going vessel corrosion. This task included data on welding metallurgy, on coatings and on cathodic protection.

3. Make direct contact with those authors from Item B.2. who obviously could make a major contribution to the study.

4. Visit a variety of Canadian and foreign shipyards and organizations operating ice-going vessels to obtain their experience in all aspects of hull corrosion and corrosion control.

5. Compile all data obtained and interpret it to develop recommendations for good construction and operation practice.

C. Findings

1. General

Corrosion has been a major problem for ice-going ships because the usual coatings are quickly removed by ice abrasion. The external elements of a conventional cathodic protection system are also subject to ice damage, particularly the large anodes of a passive system, so that their omission has been common practice. Weld lines are subject to preferential wasting, seriously weakening the structure and requiring costly repair; also the heavy corrosion roughening of plate surfaces in contact with ice gives rise to a very high friction coefficient and substantially increased icebreaking effort compared to a smooth surface.

High performance coatings have recently been developed which, if properly applied will stand up to several seasons of ice-breaking with only minor damage. In addition, impressed current cathodic protection systems have been developed which are effective in an icebreaking environment, so that corrosion is controlled or greatly reduced over the 15 - 20% of hull surface which is expected to be exposed due to coating system damage. Welding materials and procedures have also been developed so that preferential attack on the weld and heat affected zones is greatly reduced.

Thus hull corrosion of icebreakers can be reduced to a threat rather than an actual problem. Typically it is reported that the Finnish Board of Navigation, with ten icebreaking vessels, previously had to re-weld corroded welding every ten years. Now, with a high performance coating and a cathodic protection system which complement each other, the Board is no longer concerned about corrosion, and plan to recoat at five year intervals.

2. Weld and Weld Zone Corrosion

Weld and weld zone corrosion is potentially serious on many ice-going vessels, and has led to major studies, particularly by the northern European ship fabrication industry. Canadian operators have not encountered serious weld heat-affected-zone corrosion in the past but recent use of improved construction materials has led to incidence of severe weld zone attack. Some specific findings are:

(a) Control of unprotected weld corrosion is achieved by using more noble weld consumables.

(b) Unprotected weld zone (HAZ) corrosion can be controlled by using steels with low manganese content and appropriate welding-heat inputs.

(c) Canadian vessels built to date have not addressed corrosion control of the weld and weld zone by fabrication procedures.

(d) All possible attention should be paid to the cosmetics of finished welds. It has been demonstrated that slag, weld splatter, and irregular weld contour can affect the ability of paint films to adhere, and wear is accelerated over protruding weld beads.

3. Coatings

(a) The only high performance coatings with significant successful operating experience in 1984 are the high solids Inerta 160 (epoxy) and Zebron 1984 the former being substantially more widely used. As well as success both have also experienced costly failures, attributable to some aspect of preparation, application, or curing being improperly carried out. It is unrewarding to apply any but the best possible coating, proven by actual performance on ships.

(b) As well as preventing the high friction coefficient due to extreme roughening of hull steel by corrosion, the high performance coatings give some improvement over bare smooth steel. Differences in friction coefficient against ice for different coatings have been measured in laboratory tests but are relatively insignificant compared to the improvement over rough corroded steel. In such cases, marked differences in icebreaking performance attributable to reduced friction are reported, and fuel savings of over 10%.

(c) High performance coatings require a major investment in materials, facilities, personnel training and drydock time.

(d) The investment is at high risk, which is alleviated only by first class quality control procedures supported by solid contractual arrangements which clearly designate financial responsibility for any departure from established procedures, as well as other responsibilities of the contractor and the performance expected.

(e) Inspection by an independent agency during surface preparation and coating application and curing is necessary to avoid a conflict of interest by the coating manufacturer. The inspection agency should be appointed by the owner.

(f) Ship hulls must be thoroughly cleaned and prepared prior to the application of a high-performance coating, including dry abrasive blast to bare metal to produce at least a near-white finish with an anchor pattern of 75 microns.

(g) Coatings must be applied strictly according to the manufacturer's specifications. In addition to proper mixing and application techniques, coatings are sensitive to temperature of air and metal surface, relative humidity and dew point, curing temperature and time for curing.

(h) The design and use of protective shelters for cleaning and coating vessels in drydock vary widely. No standard design has evolved, the equipment used being peculiar to each shipyard. Typically, such shelters are constructed from lumber and tarpaulins or from plywood sheeting and angle iron. Heat for shelters is usually provided by direct gas firing (condensation potential) or by indirect gas fired heaters. The costs of shelters vary widely. Typically, on a large icebreaker 1000 man hours will be required to hoard the vessel. Shelter ventilation is required to avoid accumulation of explosive solvent vapors.

(i) There appears to be a need for a concentrated effort to acquaint the Canadian shipbuilding industry with the specific needs of coating ice-going vessels. Such a program should include technology transfer by coatings companies, ships operators, research agencies and consultants. The current study has shown that most shipyards do not have a rigorous quality control program for high-performance coating application.

4. Cathodic Protection

(a) Cathodic protection is recognized as an integral part of hull corrosion control on ice-going vessels. Such protection is probably more valuable on ice-going vessels than on those vessels which operate under ice-free conditions and which undergo less coating damage.

(b) Cathodic protection can be provided by impressed current systems or by galvanic anodes. The former are favoured because galvanic anodes have limited current output and are susceptible to mechanical damage (usually large numbers of passive galvanic anodes are needed for adequate current output).

(c) Successful cathodic protection depends on application of a high-performance hull coating to provide current distribution and to reduce protective current level.

The system design should be based on established current densities and an assumed coating damage of 20%. This figure will cover such bare areas as shafts and propellors.

(d) The synergism of high-performance coatings and cathodic protection is evident and is recognized by all ship operators. Cathodic protection controls corrosion where coatings are damaged and prolongs coating life by inhibiting underfilm attack at breaks and pinholes. The coating provides for effective current distribution with minimal size of cathodic protection components exterior to the hull.

SOMMAIRE

A. OBJECTIFS

La présente étude, réalisée a la demande du Centre de développement des transports (CDT) de Transports Canada, a consisté à faire un tour d'horizon des méthodes couramment utilisées pour protéger la coque des navires brise-glace contre la corrosion. Etant donné que la corrosion des coques provient de causes multiples qu'il importe de bien comprendre si l'on veut les combattre efficacement, il a fallu procéder de façon exhaustive allant des techniques de sondage, revêtements protecteurs et conditions d'application de ces derniers à la protection cathodique. Le CDT avait demandé que la recherche débouche sur un compte rendu qui puisse servir de guide en matière de construction et d'exploitation de navires brise-glace et qui, en outre, se prêterait à des mises à jour successives.

Le contractant, B.H. Levelton and Associates Ltd., a obtenu le concours de la firme Peter S. Hatfield Ltd., architectes navals, dans le domaine des codes de construction navale, des méthodes de mécano-soudage et dans divers autres domaines portant plus particulièrement sur les navires brise-glace. Pour sa part, le contractant a mis à profit son savoir-faire dans les domaines des techniques de soudage, de la lutte contre la corrosion, des revêtements et de la protection cathodique; en outre, il a rassemblé les données nécessaires et rédigé le compte rendu.

B. MODE OPERATOIRE

La recherche a été divisée en une série de tâches, la plupart se déroulant plus ou moins simultanément:

1. Recueillir des données sur les codes de construction navale, y compris celles provenant de Peter S. Hatfield Ltd., des chantiers navals et des forces armées navales du Canada et des Etats-Unis.

2. Mener une recherche documentaire dans le domaine de la corrosion des navires brise-glace et s'étendant à d'autres domaines comme la métallurgie du soudage, les revêtements et la protection cathodique.

3. Prendre contact avec les auteurs d'ouvrages repérés en B2, qui pourraient faire avancer la recherche.

4. Visiter divers chantiers navals au Canada et ailleurs ainsi que les armateurs de navires brise-glace afin d'y glaner des connaissances portant sur la corrosion des coques et les moyens de l'enrayer.

5. Compiler toutes ces données et les utiliser pour formuler des recommandations visant à proposer des méthodes de construction et des procédures d'exploitation qui soient saines.

C. RESULTATS

1. Généralités

Les navires brise-glace sont très sensibles à la corrosion dans la mesure où les revêtements qui en protègent la coque peuvent être rapidement érodés par le frottement avec les glaces. Ces dernières peuvent de plus provoquer des avaries dans les éléments extérieurs faisant partie d'un système classique de protection cathodique, notamment les anodes de fortes dimensions dans le cas d'un système passif, au point que leur rejet est devenu pratique courante. Les lignes de soudure peuvent subir une attaque préférentielle qui affaiblit gravement la structure et coûte cher à éliminer. Enfin, les parties de la coque en contact avec les glaces deviennent très rugueuses à cause de la corrosion qui finit par les ronger ce qui augmente considérablement le coefficient de frottement et, par conséquent, l'énergie requise pour franchir une surface glacée comparativement à une surface lisse.

Depuis quelque temps, on trouve sur le marché des revêtements de haut rendement qui, appliqués avec toute la rigueur nécessaire, peuvent résister à plusieurs saisons de navigation dans les glaces tout en ne subissant que de légères avaries. Il existe également des systèmes de protection par courant imposé qui se révèlent efficaces sur un navire brise-glace en permettant d'enrayer ou de réduire considérablement la corrosion des parties de la coque qui perdent leur revêtement à cause du frottement dû aux glaces et qui représentent entre 15 et 20 p. 100 de la surface totale. Enfin, il existe des techniques et des matériaux de soudage susceptibles de réduire considérablement les attaques préférentielles que subissent les cordons de soudure et les zones voisines affectées thermiquement.

Les techniques de prévention sont maintenant telles qu'elles font de la corrosion une menace à conjurer plutôt qu'un vrai problème. Exemple: les dix navires brise-glace appartenant à la Commission de navigation de la Finlande qui devaient autrefois être réparés à intervalle de dix ans pour éliminer les parties de la coque corrodées et qui, maintenant, grâce à l'association d'un revêtement haut rendement avec une protection cathodique, n'exigent plus qu'un nouveau revêtement tous les cinq ans.

2. Cordons de soudure et zones corrodables

Les cordons de soudure et les zones affectées thermiquement sont potentiellement très corrodables. C'est un problème qui a fait l'objet de recherches approfondies, notamment dans les chantiers navals d'Europe septentrionale. Au Canada, jusqu'à récemment, la corrosion des zones affectées thermiquement ne s'était pas manifestée de façon inquiétante, mais depuis l'emploi en construction navale de certains matériaux améliorés, des cas graves de corrosion des cordons de soudure ont été signalés. Voici quelques-unes des constatations particulières faites:

a) Les cordons de soudures mis à nu résistent mieux à la corrosion si on utilise des métaux d'apport plus nobles.

b) Les zones affectées thermiquement résisteraient mieux à la corrosion par l'emploi d'aciers à faible teneur en manganèse et par le réglage approprié des apports thermiques au sondage.

c) Au Canada, la question de la résistance à la corrosion des cordons de soudure et des zones affectées thermiquement n'a pas encore été abordée sous l'angle des méthodes de mécano-soudage.

d) Une attention rigoureuse doit être apportée à la finition des cordons de soudure de manière à accroître l'adhérence des peintures de revêtement, qui peut être affaiblie par le laitier, les projections de soudure et l'irrégularité dans la forme des soudures. Quant à l'usure du revêtement, elle est plus marquée là où la soudure fait saillie.

3. Revêtements

a) Les seuls revêtements haut rendement à avoir connu du succès en 1984 ont été les résines Inerta 160 (époxydiques) et Zébron 1984, toutes deux à forte teneur en solides, la première étant toutefois de loin la plus utilisée. Cependant, ces résines ont connu également de coûteux échecs, attribuables au fait que tel ou tel détail du processus de préparation, de mise en oeuvre ou de réticulation a été négligé. Quoiqu'il en soit, d'après les résultats constatés en service, c'est courir à l'échec que d'utiliser d'autres revêtements que le meilleur.

b) Les revêtements haut rendement permettent de réduire le coefficient de frottement dans le cas non seulement des tôles d'acier rongées par la corrosion, mais aussi des tôles lisses et nues. Les essais en laboratoire ont dégagé des écarts dans la réduction du coefficient de frottement dû aux glaces apportée par divers revêtements, mais ces écarts sont négligeables lorsqu'on les compare à l'amélioration apportée par ces mêmes revêtements sur des tôles que la corrosion avait rendues rugueuses. On a constaté dans certains cas des performances nettement améliorées durant le franchissement des zones chargées de glaces, résultat de la diminution du coefficient de frottement, avec, en plus, des gains de consommation de combustible pouvant dépasser 10 p. 100.

c) Les revêtements haut rendement nécessitent un capital d'investissement élevé: matériaux, installations, apprentissage et temps d'application.

d) Le risque financier encouru ne peut être atténué que par des procédures rigoureuses de contrôle de la qualité, précisées sans équivoque possible dans les cahiers des charges qui doivent également prévoir les modalités de détermination des responsabilité financières devant sanctionner toute infraction à la procédure établie, les tâches devant être exécutées par le contractant ainsi que les résultats escomptés.

e) L'armateur devrait confier à une agence indépendante le soin de contrôler la qualité de l'exécution des travaux (préparation des surfaces, application du revêtement et réticulation) dans le but d'éviter que le fabricant du revêtement ne se place dans une situation de conflit.

f) Le nettoyage et la finition des surfaces précédant l'application du revêtement haut rendement doivent être faits avec soin, par un grenaillage à sec devant mettre à nu le métal, produire une finition "presque blanche" et réaliser une couche d'accrochage d'une rugosité de 75 micromètres.

g) L'application du revêtement doit se faire en stricte conformité des instructions du fabricant. En plus d'une bonne préparation du mélange et du mode d'application, d'autres facteurs influent sur la qualité du revêtement: température de l'air et du métal, humidité relative et point de rosée, température de réticulation et laps de temps laissé à cette dernière.

h) La conception et l'usage des abris que nécessitent les travaux de nettoyage et de revêtement des navires au raboub varient grandement. Faute d'équipement standard, les chantiers navals utilisent un équipement qui leur est propre. D'habitude, les abris sont faits de bois et bâchés, ou de contreplaqués assemblés par des cornières. Ils sont chauffés, soit par des radiateurs autonomes au gaz avec le problème de condensation que cela implique, soit par des générateurs à combustion indirecte. L'aspect financier est, lui aussi, très variable. Pour mettre un gros brise-glace sous abri, un millier d'heures-personnes est nécessaire. Enfin, il faut prévoir une ventilation suffisante pour éviter l'accumulation des vapeurs explosibles dégagées par les solvants utilisés.

i) Un effort concerté semble nécessaire pour initier les chantiers navals à la protection des navires brise-glace contre la corrosion. Ce programme devra comporter un transfert de technologies de la part des fabricants de revêtements protecteurs, des armateurs et des établissements de recherche et des consultants spécialisés dans le domaine. La présente recherche a démontré que la plupart des chantiers navals n'ont pas de programme pour le contrôle rigoureux de la qualité dans l'application des revêtements haut rendement.

4. Protection cathodique

a) La protection cathodique fait désormais partie intégrante de l'arsenal de la lutte contre la corrosion des coques de navires, surtout s'il s'agit de navires brise-glace plus sensibles aux avaries du revêtement que d'autres qui n'ont pas à franchir des eaux chargées de glaces.

b) La protection cathodique peut se faire par courant imposé ou par des anodes galvaniques. La préférence va au premier de ces deux procédés étant donné que le deuxième souffre du double défaut de la faible portée des anodes et du risque d'avaries mécaniques (en général, pour réaliser une zone d'immunité étendue, un nombre élevé d'anodes doit être mis en place).

c) L'association d'une protection cathodique et d'un revêtement protecteur haut rendement peut être avantageuse car elle permet une bonne distribution du courant et une réduction des densités de courant nécessaires. Le choix du système doit reposer sur des densités de courant connues et sur l'hypothèse que les avaries du revêtement ne dépassent pas 20 p. 100 de la surface totale à protéger, y compris les parties nues comme les arbres et les hélices.

d) L'effet de synergie qu'apporte l'association d'une protection cathodique à un revêtement haut rendement est évident pour les armateurs. La protection cathodique enraye la corrosion sur les parties de la coque qui ont perdu leur revêtement et prolonge la durée de vie du revêtement en inhibant la corrosion du métal sous-jacent aux endroits où le revêtement présente une discontinuité ou des piqûres. Pour sa part, le revêtement permet une bonne distribution du courant et, parallèlement, la possibilité de réduire au minimum la taille des éléments du système de protection cathodique qui se posent sur la coque.

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I. INTRODUCTION

A. OBJECTIVES

The Transportation Development Centre (TDC) of Transport Canada commissioned B.H. Levelton and Associates Ltd. to produce a state-of-the-art report on the methods used to control corrosion on ice-going vessels and also to elucidate the basic causes of localized corrosion at weld zones. It was intended that the report would serve as a reference text for construction and operation of ice-going vessels. Since the causes of corrosion and the basic science of welding, coatings and cathodic protection must be appreciated to deal with corrosion control, the study has necessarily progressed beyond the simple concept of a manual. Thus, each main section deals with the technology of the subject matter in sufficient detail to understand what measures must be taken to control corrosion associated with it.

B. THE STUDY TEAM

The study team was selected to provide knowledge and experience in corrosion and corrosion control, in ice-going vessel construction, and in ice-going vessel operation. B.H. Levelton and Associates Ltd. was the principal contractor, responsible for directing the study and for evaluating corrosion and corrosion control technology applicable to ice-going vessels.
Peter S. Hatfield Ltd., marine architects, was a subcontractor providing basic information on construction codes and methods of ship building. Canadian Marine Drilling Ltd. (Canmar) through Mr. J.L. Strand provided information on ice-going vessels continuously operated and maintained in the Canadian Arctic.

C. STUDY METHODOLOGY

The study work program was arranged to satisfy the requirements of Transport Canada, viz,

- to evaluate the technology and experience in corrosion and corrosion control on ice-going vessels;

- to develop, where possible, recommended practices for construction and maintenance of corrosion control.

It was recognized at the outset that the three factors involved in hull corrosion - weld metallurgy, coatings and cathodic protection - were interrelated and could not be considered in isolation when considering hull corrosion control. Corrosion of high-strength tough steels used in icebreakers can be severe in welds and weld heat-affected zones and, in the absence of a protective coating and cathodic protection, can threaten the integrity of the hull. Thus, it is essential that the best available weld metallurgy be used to reduce attack by the basic corrosion mechanism even though the two corrosion control processes can also be used to reduce damage. Protective coatings on ice-going vessels provide a dual function in protecting the hull from corrosion at all points and at welds in particular, and in reducing friction between hull and ice. However, coatings are damaged by ice and damage is most severe where the hull surface is rough such as at welds which are not ground smooth. Coatings, therefore, may protect the bulk of the hull surface but may not control attack at the most vulnerable areas, viz, at the welded joints. Cathodic protection provides a third level of protection, again acting in a dual function. First, it protects the steel bared where ice damages the coating, and, second, it controls underfilm corrosion of protective coatings at damage sites. Thus, it protects any bare steel and prolongs coating life. In return, the existence of a sound protective coating allows a cathodic protection system to function effectively by promoting good current distribution and by reducing the size of the cathodic protection system to a manageable size. On ice-going vessels any projection on the hull is a site for potential damage.

It is evident that cathodic protection and protective coating exhibit true synergism. On ice-going vessels, as in other installations subject to corrosion, one form of protection should not be considered without the other.

While hull corrosion becomes a problem only if the protective coating is damaged and if the cathodic protection system becomes inoperative or cannot provide sufficient current to polarize bare hull areas, it must be recognized that at times both corrosion control measures may be inoperative for considerable periods. Thus, it is logical to construct the hull using a metallurgy which minimizes localized attack at and near welds when the normal control measures are not operating.

The report deals individually with each of the three major factors affecting hull corrosion. The interrelationships between the three are developed within the text.

The information presented in this report is based on work done in a series of tasks shown below:

1. Assemble all pertinent data on ship construction codes and maintenance methods. Peter S. Hatfield Ltd. provided the core information which was supplemented by visits to ship construction facilities and correspondence with authorities concerned with ice-going vessel construction.

2. Conduct a literature survey to obtain all pertinent data on ice-going vessel corrosion. While this literature survey included all major parameters, much of the work centered on weld metallurgy since this is the area most affected by primary research studies.

3. Visit ship construction and maintenance facilities throughout Canada, U.S., and Europe specifically to establish construction processes, coating technology and cathodic protection design.

4. Establish contacts with agencies which have specialized in corrosion control on ice-going vessels, such as:

   (a) The U.S. Coast Guard;

   (b) The Finland Board of Transportation.

5. Compile all data and interpret it to develop recommendations for proper construction and operation.

D. SCOPE OF WORK

1. Weld Metallurgy

The causes of preferential weld zone corrosion (both weld and heat affected zone) and effects of various welding procedures and steel compositions on such corrosion are studied. It is implicit that the required physical properties of the hull plate for service in ice-covered waters will be maintained.

2. Coatings

The performance of heavy duty or high performance coatings when subjected to the unusual mechanical abuse encountered in ice-covered waters is evaluated. Specific coatings that are being used successfully in ice are identified. The factors affecting the coating performance are studied, including surface preparation, application conditions, resistance to abrasion and impact, and compatibility with cathodic protection.

3. Cathodic Protection

The performance of cathodic protection systems in ice-covered waters is investigated. The components of successful designs are detailed, including protection against mechanical damage, maintenance of a protective potential, and reliable service between dry dockings.

II. WELD CORROSION

A. CAUSES FOR CONCERN

Weld corrosion can be defined as selective corrosion of the deposited weld metal or heat-affected zones (HAZ) of the base metal which has had its structure altered by the heat of welding.

Weld corrosion can occur in the absence of or in conjunction with general corrosion of the plate material. The seriousness of weld corrosion and the reason for its being treated almost independently of general plate corrosion lies in the localized nature of the attack. When the depth of corrosion penetration is the same in both weld zone and parent plate, there is no reason for special concern. However, in many cases, the depth of corrosion penetration is much greater in the weld zone. Thus, a hull which otherwise might be in good structural condition can, in fact, be severely weakened due to localized areas of significantly reduced plate thickness.

Coating systems that are applied to the hull do not adhere well to a rough weld-bead surface. Local areas of corrosion may develop at these points, and further undercutting and damage to the coating will develop.

Repairs to damaged weld seams are costly and, furthermore, increase the risk of incorporating an injurious defect in the weld seam. It is more difficult to produce a first-class joint during repair welding than during actual fabrication. Also, the repair weld incorporates one more metallurgical dissimilarity (welding parameters may be different than actual construction) into the hull and, thus, increases the probability of localized corrosion.

To summarize, there are four major reasons why corrosion of weldments is of particular concern:

1. Deep, localized corrosion can result and weaken an otherwise sound hull;

2. Because it is localized, weld corrosion may not be detected readily, particularly if the plate has undergone a light, general corrosion;

3. Coating systems may not totally protect a rough weld bead;

4. Repair welding has economic and metallurgical disadvantages.

B. NATURE OF WELD CORROSION

1. Differences in Corrosion Potential

It has been well established that selective weld corrosion is due to differences in the corrosion potential between the weld zone and the parent plate(1 to 4). A galvanic couple is formed whereby the weld becomes the anode and the parent plate is the cathode. It has been demonstrated that in seawater, the corrosion current is controlled by oxygen diffusion to the cathode(5), which in this case, can be the entire portion of the hull under water. The unfavorable area ratio of large cathode to small anode can give rise to very large current densities leaving the anode and, therefore, a high degree of localized corrosion penetration.

The variation in corrosion potential is caused primarily by microstructural dissimilarities between the weld, HAZ, and parent plate. The microstructure of the weld is, in fact, a quickly cooled cast metal that contains columnar grains, dendrites, and areas of microsegregation. The heat-affected zone frequently has a structure similar to that of steel plate quickly cooled from a red heat. Both are different from the ferrite/pearlitic structure of hot rolled plate commonly used in ship construction.

2. Effects of Operating Environment

Uusitalo demonstrated that the characteristics and operating environment of icebreaker operation give rise to increased corrosion of the steel hull generally and greatly increased corrosion of the weld seams specifically(1, 2). The tendency of weld seams to be anodic relative to steel plate have already been discussed. In icebreaker operation, this galvanic interaction between weld seam and parent plate is greatly magnified.

(a) Velocity

Laboratory measurements have shown that when welded-steel samples were exposed to flow rates up to 5 m/s, weld-metal loss due to galvanic corrosion increases greatly. A change in the flow rate from 0 to 3.6 m/s caused a 10 to 15-fold increase in the corrosion rate of the anode (weld). The rates of weld-metal corrosion produced in this study (1.3 to 2.0 mm/y) were comparable to those observed on operating icebreakers (3 to 5 mm/y). Presumably, the increased water velocity leads to better depolarization of anodes through improved oxygen transfer.

(b) Abrasion

The abrasive action of the ice against the hull of the vessel constantly removes corrosion products from its surface. Such corrosion products reduce corrosion rates in much the same way as a protective coating operates.

They also decrease access of oxyen to the metal surface and thereby decrease polarization.

(c) Water Temperature

The colder the water, the greater the solubility of oxygen in the water. Since oxygen is a depolarizer, the higher oxygen level will accelerate the corrosion process, but water conductivity decreases with temperature and so the effect of oxygen level may be offset.

Uusitalo in his studies found that as the oxygen content of seawater increased, the corroding potentials of many weld metals became more negative (anodic) with respect to the parent metal. Because of this, their tendency to corrode galvanically is increased. When the temperature of the test solution was decreased from 25°C to 0°C, it was found that weld metal previously cathodic with respect to its parent plate became anodic.

C. MICROGALVANIC CORROSION

Selective corrosion of the weld zone is due to galvanic action between anodic and cathodic zones. Furthermore, it has been adequately demonstrated by many investigators that this corrosion is caused primarily by the development of macrogalvanic cells between the weld and parent metal. However, there is justification for being concerned about factors that promote corrosion on a microgalvanic scale as well, particularly on coated vessels. In many cases, it may be microcorrosion cells that result in the initial blistering and damage of a protective coating.

The occurrence of microgalvanic corrosion cells can be attributed to the presence of mill scale or other foreign material on the weld, electrode constituents and slag in the weld(6), oxide precipitates in the weld metal(7), and sulphide inclusions within the parent plate(8).

Bradley and Rowlands(7) reported that weld specimens prepared using low-hydrogen electrodes corroded 1-1/2 to 3 times faster than welds made by electrodes classed as rutile types. They attributed this increased corrosion rate to a high volume fraction of FeO/Fe_3O_4-type precipitates in weld metal from low-hydrogen electrodes. It had been proposed by previous investigators that this corrosion susceptibility might be due to electrolytic action between the iron-oxide precipitates and iron.

Slag residues are widely held to influence at least the initiation of pitting, since they disturb the electrochemical continuity of the metal surface. In the work previously referred to, Bradley and Rowlands investigated the effect of slag residues on the tendency of painted steel weldments to pit and cause damage to the paint film. The findings of the study were as follows:

1. Most slags are conductive and have potentials more electropositive than mild steel. The investigation further concluded that:

   > "In view of the potential differences observed between mild steel and most weld slags, it could reasonably be forecast that galvanic corrosion would occur under permeable paint films and would result in cathodic blistering around slag particles".

2. Machine wire brushing and/or grit blasting did not adequately remove slag residue. Exposure to seawater of painted panels that were prepared in either of these ways resulted in paint blistering after eight weeks.

3. Paint blistering was more pronounced on steel surfaces adjacent to low-hydrogen electrode welds than welds prepared with rutile electrodes.

D. MACROGALVANIC CORROSION

1. Corrosion of the Weld Metal

The electrochemical measurements conducted by Uusitalo were on a "macro" scale and demonstrated that weld deposits of chemical composition similar to the base material can show corroding potentials that are negative relative to the base material. Furthermore, this potential difference changes in the Arctic so that welds can actually be cathodic in warmer waters and become very anodic in colder Arctic waters.

It is probable that the reason for this anodic behavior of weld metal is the vast difference in microstructure between the weld and base material. For instance, it was observed by Campbell(9) that the last weld beads deposited in a butt weld exposed to icebreaking service corroded at a much greater rate than previously deposited weld beads. The final weld-bead deposits showed a large-coarse columnar structure, while previously deposited weld beads showed a refined structure. Polished and etched cross-sections of the weld joint clearly showed that the corrosion took the form of longitudinal grooves that followed the pattern of columnar structure contained in the final capping passes.

The most expedient solution to the problem of anodic weld metal is the use of welding electrodes that are more noble than the base material. This appears to have been investigated first by Valanti(10), who experimented with different types of ship plate and consumables. Since it was acknowledged that the operating environment of an icebreaker increased weld corrosion, Valanti developed a test method that would simulate these conditions. The apparatus in the so-called ESAB, or corrosion-tank test, consists of a horizontal rotating disc onto which test samples are attached. The samples are immersed in a seawater solution for several months. No electrochemical measurements are taken. Corrosion is measured by weight loss and depth of penetration.

ESAB AB of Sweden developed a corrosion-resistant welding electrode using the data produced by Valanti. This electrode was initially called OK48.23 and was in use as early as 1966. The chemical composition of this electrode is shown in Table II-1. The important components of the electrode are silicon, copper, and nickel. Copper is well known for its ability to increase the corrosion resistance of steels as is nickel. Uusitalo reported that steels of high silicon content showed increased corrosion susceptibility. It has also been reported(11, 12) that a low manganese/silicon ratio reduces corrosion resistance of a weld seam due to the effect on the viscosity of the molten weld pool.

The ESAB corrosion-resistant electrode is now widely used for icebreaker fabrication with reports of success in reducing hull weld-area corrosion.(13).

2. Corrosion of the Heat-Affected Zone

(a) General

Corrosion of the heat-affected zone has been reported on Canadian icegoing vessels, but at this time has not posed the same magnitude of problem as weld metal corrosion. This may be due to the fact that the higher manganese steels, which most investigators believe promote HAZ corrosion, have only recently been used for ship construction in Canada. Also, until completion of the BeauDril vessels, alloyed welding electrodes had not

TABLE II-1

CHEMICAL COMPOSITION
OF THE INITIAL ESAB CORROSION-RESISTANT ELECTRODE
OK48.23

ELEMENT	WEIGHT %
Carbon	0.08
Manganese	0.70 - 1.00
Silicon	0.20 - 0.35
Nickel	0.40 - 0.50
Chromium	---
Copper	0.40 - 0.60

been used. Previously, E7018 electrodes were used predominantly, which would have left both the weld area and the heat-affected zone anodic to the parent material. Hence, any corrosion of the heataffected zone would not be pronounced (due to the larger anode area) or as noticeable. In fact, it was not until a corrosion-resistant welding electrode was used that Finnish investigators first noticed the existence of heat-affected zone corrosion.

While HAZ corrosion has not been established as a major problem at this time in Canadian vessels, it may become a serious problem, replacing that of weld metal corrosion.

Corrosion of the HAZ was first observed in 1966 on the icebreaker Kiev(14). Narrow corrosion grooves adjacent to the weld seam to a depth of 3 mm occurred after only six months operation. The corrosion damage occurred in steels in which high strength and weldability were achieved by means of high manganese and low carbon content. Welding had been carried out with the recently developed OK48.23 welding electrode. A chemical analysis of the plate is shown in Table II-2.

The discovery of HAZ corrosion sparked a great deal of investigation by the research arms of Rautaruukki Oy Steel of Finland and Esab Electrodes of Sweden.

The initial investigation by Valanti indicated that the high rate of HAZ corrosion was due to changes in the crystalline structure of the parent metal brought about by welding heat(14). These changes in structure resulted in the HAZ becoming electronegative to the base metal and filler material. Subsequent investigations set about confirming and quantifying Valanti's observations.

Test methods employed by the researchers were the ESAB corrosion-tank test and the anodic dissolution

TABLE II-2

ANALYSIS OF 09G2 STEEL PLATE USED ON THE VESSEL "KIEV"

ELEMENT	WEIGHT %
Carbon	0.12
Silicon	0.17 - 0.37
Manganese	1.40 - 1.80
Nickel	0.30 max.
Chromium	0.30 max.
Copper	0.30 max.

described by Saarinen and Onnela(15). Saarinen's test method consisted of potentiostatic anodic dissolution of heat-affected zones artificialy produced by the Noren weld-hardening method and had the distinct advantage of giving quantitative results after a very short test period. In several studies, both test methods were employed and showed that results of long-term corrosion testing (ESAB test) could be anticipated and quantified using the anodic dissolution test.

A third test method used in the earlier HAZ corrosion studies by Raty et al(16) was the socalled current-ratio test. The test method basically consisted of maintaining constant anode potentials and measuring the equilibrium value of the current ratio between the test anode (artificially produced from a Jominy end-quench sample) and a standardized anode.

(b) Review of Investigations into HAZ Corrosion

A report produced in 1968 by Raty et al(17) examined the microstructural characteristics of steel samples showing heat-affected zones corroded by six months exposure to the corrosion-tank test. They reported the microstructure of the heat affected zone to be composed of so-called "massive ferrite", which can be similar in appearance to martensite in that it frequently forms in parallel bands.

Raty and coworkers furthered this hypothesis in a report describing the the current-ratio test. Their conclusions are as follows:

- Austenite containing up to 0.10 wt% carbon can transform to ferrite massively without partition of carbon. Carbon is in solution or is "quenched-in";

- Anodic behaviour of HAZ zones occurs because of the instability of ferrite caused by quenched-in carbon;

- Anodic behavior of the HAZ is not caused by quenched-in carbon in martensite, even though larger quantities of quenched-in carbon occur in martensite. This hypothesis was not tested;

- Corrosion of the heat-affected zone does not occur in samples of very low carbon content,

- Carbon content (up to 0.10 wt%) and rapid cooling are the major contributing factors in HAZ corrosion.

Studies by various collaborations of Saarinen, Relander, Onnela, and Alasaarela(15, 19, 20, 21) at Rautaruuki Oy Steelworks and by Lundin & Utterburg(18) of ESAB observed that martensitic and bainitic microstructures, some containing retained austenite, were responsible for the corrosion. Conducting their work at about the same time as Raty et al, these workers supported their observations quite convincingly using both the ESAB corrosion-tank test and the much faster anodic dissolution test. In all cases, the corrosion-tank test was performed using test samples containing actual welds, while the anodic dissolution tests were performed on samples containing artificial heat-affected zones produced by the Noren weld-hardening (NWH) method.

Lunden et al(18) described the corroding microstructure as consisting of either untempered high-carbon martensite or high-carbon-retained austenite in a ferrite matrix. Relander, Onnela, and Saarinen(15, 19) confirmed that the culprit microstructures were typical of low-temperature transformation of the austenite that occurred during rapid cooling of the heat-affected zones. Relander and Onnela described this microstructure as, "upper bainite, especially of retaineds austenite or martensitic-containing type, lower bainite and low-carbon cubic martensite". No observations of the so-called "massive ferrite" were made.

Saarinen(20) later described the microstructure that produced HAZ corrosion as "large, uniform areas of martensite and lower bainite, or areas of unfinished upper bainite". This upper bainitic microstructure consisted of "bainitic-ferrite fingers between which retained austenite is found".

The investigations by both Relander et al and Saarinen offer the observations made by Raty (quenched-in carbon) as supportive of their observations. However, the factors involved in producing the corroding microstructure are viewed to be both:

- Interstitials (carbon and nitrogen) in supersaturated solid solution;

- A high density of lattice defects (dislocations and vacancies).

The carbon supersaturation of ferrite proposed by Raty supports the observation that upper bainite that contains carbides (no carbon saturation) does not corrode, even though it has a high dislocation density. Also, a rapidly corroding HAZ which consists mainly of unfinished upper bainite (with retained austenite) has a high amount of carbon in solid solution both in the austenite and in the ferrite fingers, but the high dislocation density is also viewed as a necessary factor. Thus, martensite microstructures are also observed to corrode, and chemical characteristics such as high manganese content which increase hardenability, have a major affect.

(c) Plate Metallurgy and Welding Parameters

Relander and Onnela(19) conducted a series of tests in which the following variables were considered.

- Manganese: - Varied from 0.5% (typical of a low-strength structural steel) to 1.6% (typical of a medium-strength steel with enhanced toughness properties).

- Carbon Content: - Varied from 0.11% to 0.16%.

- Heat-Input Equivalent: $(\text{H.I.E}) = \frac{60.\text{I}.\text{U}}{\text{r} \quad \text{k}.\text{d}}$

where: H.I.E. = heat-input equivalent in J/cm mm$^{(1/2)}$

I = welding current in amperes

U = welding voltage in volts

r = travel speed in cm/min

d = plate thickness in millimeters

k = shape coefficient, this is two for a bead on plate weld, less for butt weld.

  - 1,000 J/cm $\mathrm{mm}^{(1/2)}$ (typical of tack welding);
  - 2,000 and 4,000 J/cm $\mathrm{mm}^{(1/2)}$ shielded metal-arc welding);
  - 8,000 J/cm $\mathrm{mm}^{(1/2)}$ (typical of submerged arc welding).

- Initial Plate Temperature (preheat): - Varied from -20°C to +300°C.

From the results of this testing, the following conclusions were drawn:

- Although there was no distinct correlation between carbon content and corrosion susceptibility, there was an indication that higher carbon contents caused increased corrosion susceptibility;

- Results from both the anodic dissolution tests on NWH test bars and ESAB corrosion-tank tests on welded plates showed that corrosion susceptibility increased greatly with decreasing heat-input equivalent;

- Corrosion attack in the areas of the HAZ heated above the lower transformation (A_1) temperature increased as the manganese content of the steel increased. In steels of low manganese content (probably less than 1%), there was no increased corrosion of the HAZ (relative to base metal), with the exception of the areas of the HAZ heated almost to the melting point (fusion line). Some of the lower manganese steels showed evidence of this fusion-line corrosion;

- In the case of corrosion-susceptible steels (high manganese content), it was found that preheating could significantly decrease the corrosion in the HAZ area.

The influence of preheat temperature, manganese content, and welding heat-input equivalent had the greatest effect on corrosion susceptibility of the heat-affected zone. The results reported by Relander and Onnela are shown in Figures II-1, 2, and 3.

Evidence that post-heat treatment can reduce HAZ corrosion has been reported by Raty, Valanti et al(17), as well as Lundin and Utterberg(18). These investigations demonstrated that annealing in the 500°C range could substantially reduce HAZ corrosion.

Saarinen(20) investigated HAZ corrosion using a variety of steel types, some of which were alloyed with vanadium and niobium. The large number of steels investigated and the incorporation of microalloying elements indicates a trend toward commercial steel development. His findings concerning the effects of heat input and manganese contents verified his earlier results in addition to the results of Relander and Onnela. He also concluded that the microalloying elements, niobium and vanadium, did not increase HAZ corrosion.

(d) The Controversy of Continuously Cast Versus Ingot-Cast Steel

At about the same time that Valanti, Raty, and Saarinen et al were conducting their early investigations

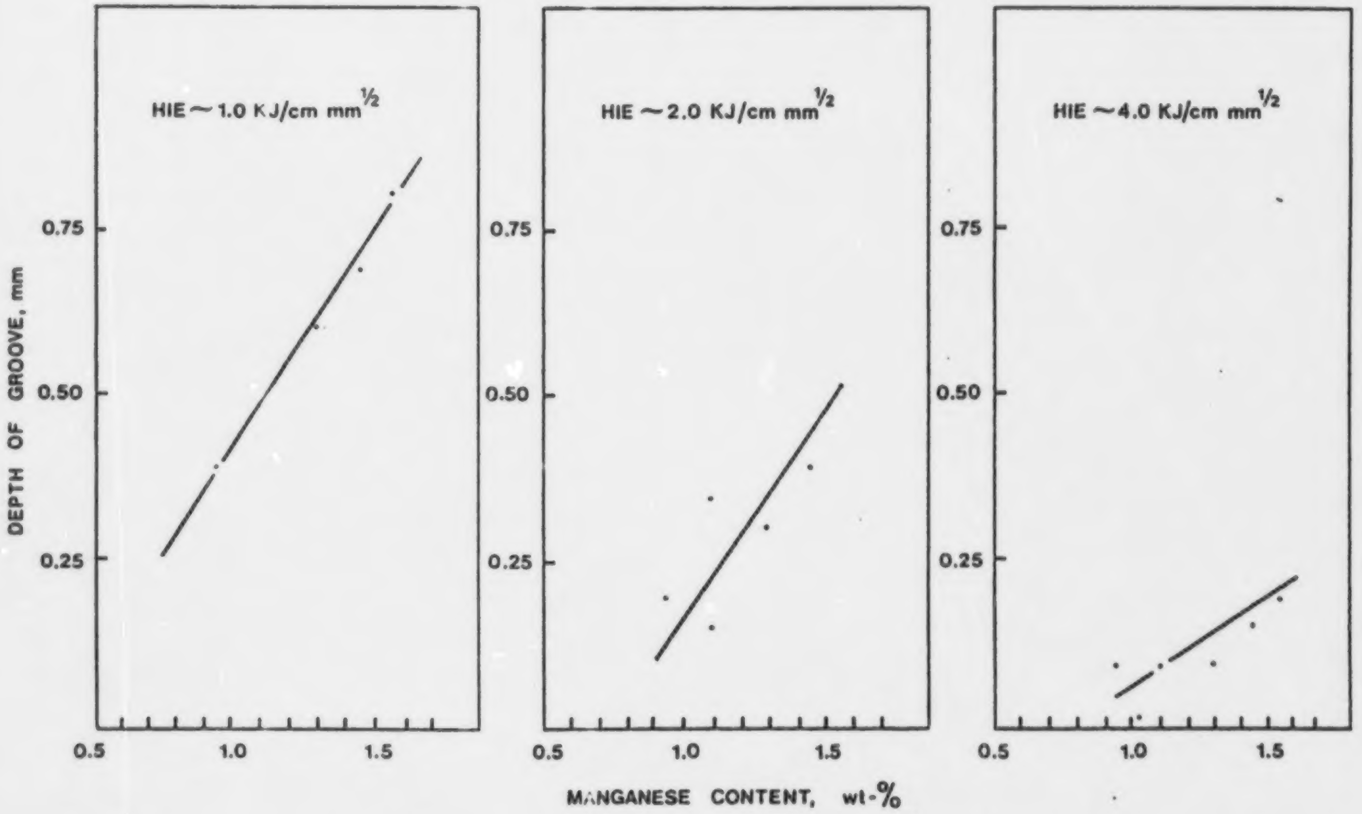


FIGURE II-1 - EFFECT OF MANGANESE CONTENT AND HEAT INPUT EQUIVALENT (HIE) ON THE CORROSION SUSCEPTIBILITY OF HEAT AFFECTED ZONES IN THE ESAB CORROSION TANK AFTER 3 MONTHS EXPOSURE.
SOURCE: RELANDER et al(19)

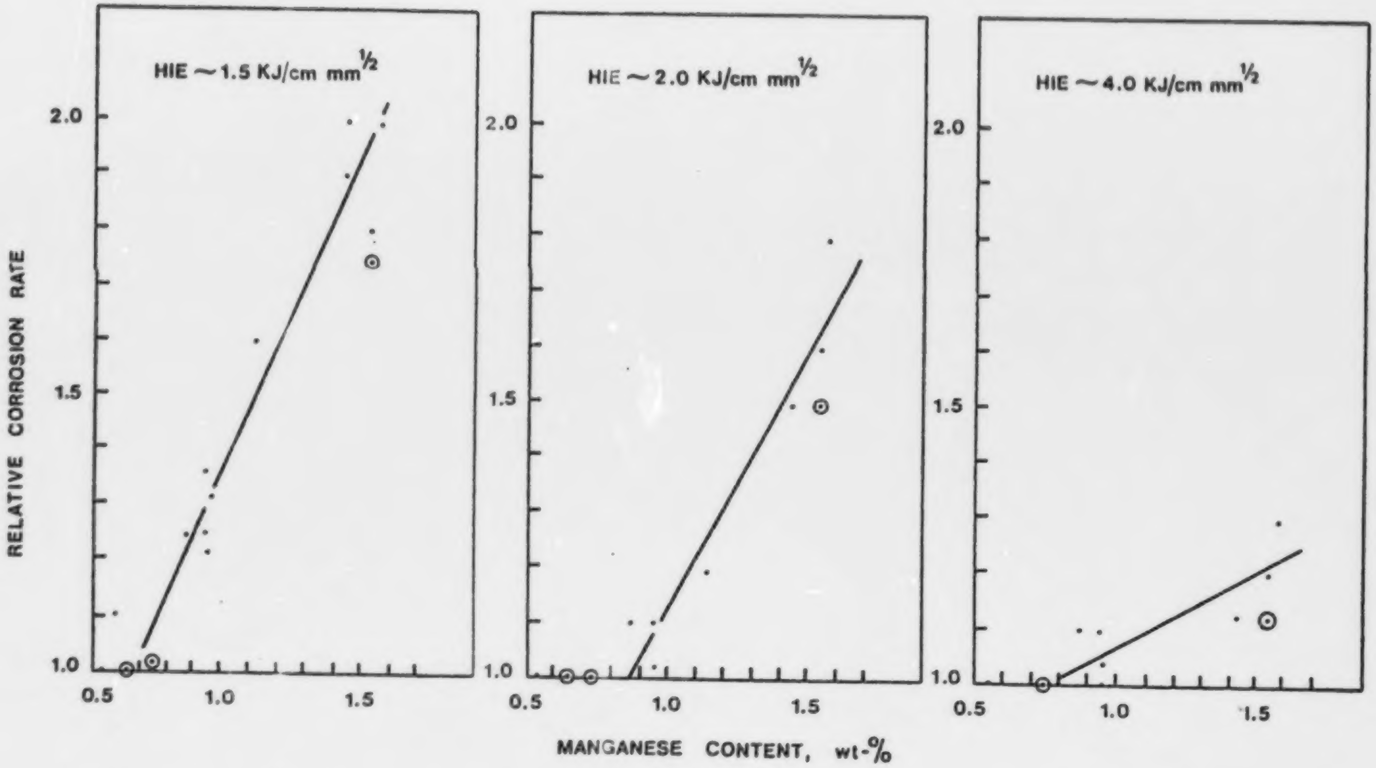


FIGURE II-2 - EFFECT OF MANGANESE CONTENT AND HEAT INPUT EQUIVALENT (HIE) ON THE CORROSION SUSCEPTIBILITY OF HEAT AFFECTED ZONES IN ANODIC DISSOLUTION OF NWH BARS. RINGED POINTS REPRESENT STEELS OF LOW CARBON CONTENT.
SOURCE: RELANDER et al (19)

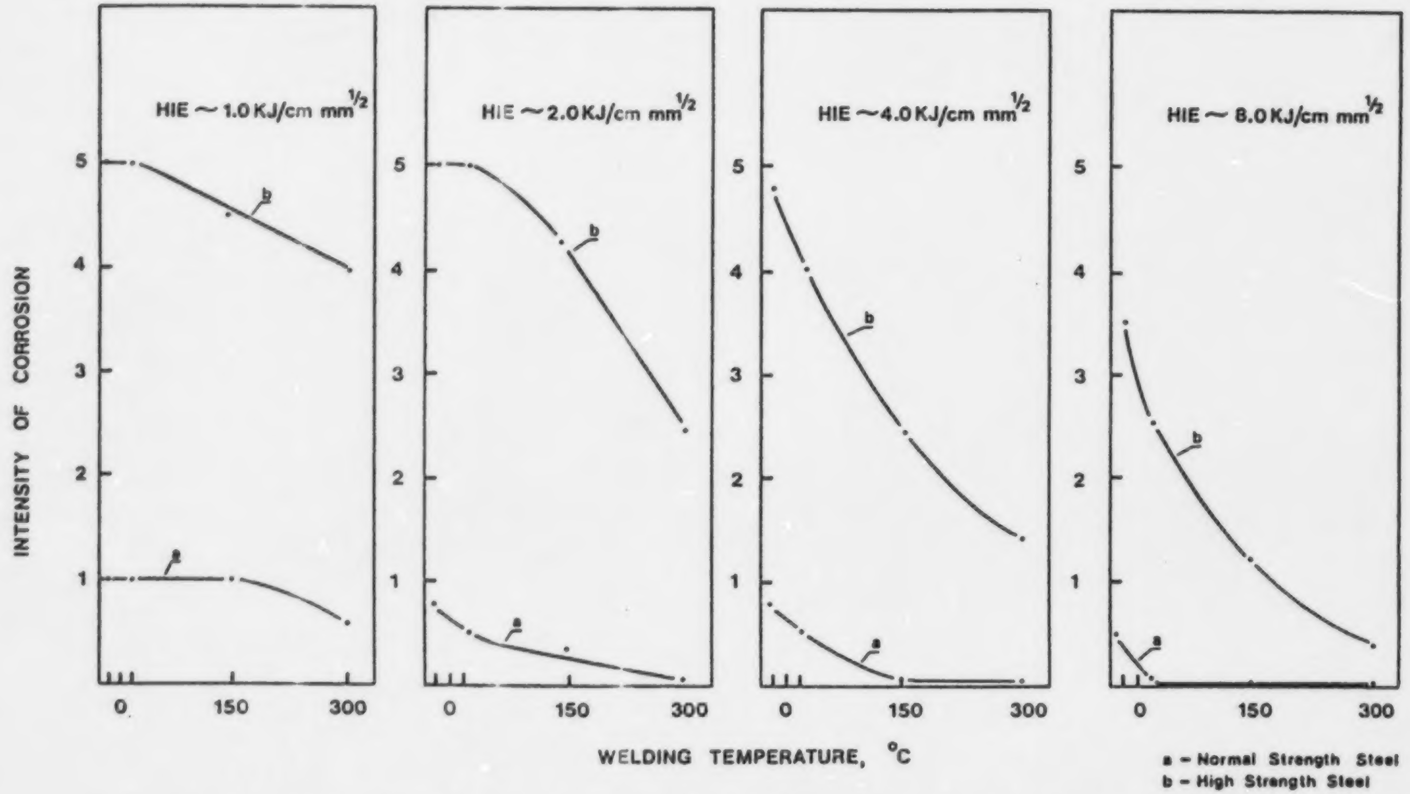


FIGURE II-3 - EFFECT OF WELDING TEMPERATURE AND HEAT INPUT EQUIVALENT (HIE) ON THE CORROSION SUSCEPTIBILITY OF HEAT AFFECTED ZONES IN ANODIC DISSOLUTION OF WELDED STEEL PLATE.
SOURCE: RELANDER et al (19)

resulting from the HAZ corrosion on the Kiev, G. Wranglen(8) was conducting a completely independent study into the observed icebreaker HAZ corrosion. His description of the vessel involved makes it apparent that the samples he investigated were also from the Kiev.

Working at the Royal Institute of Technology in Stockholm, Wranglen concluded that the extensive corrosion damage observed was due to "active sulphides" in the heat-affected zone. He further concluded that continuously cast steels were more likely to contain active sulphides than slab-cast steels. Wranglen based his conclusion on the following arguments:

- Corrosion was observed only on a certain continuously cast steel, whereas steel that was slab cast showed no corrosion. It should also be pointed out that the continuously cast steel contained 1.5% manganese, whereas the slab cast contained approximately 1.0%;

- The conclusion of Valanti and others (concerning microstructure and manganese content) did not explain the severity of the attack observed;

- He identified the finely dispersed sulphides apparent in the corroded steel as having a greater propensity for localized microcorrosion than the larger sulphides found in the noncorroded steels;

- He postulated that sulphides in continuously cast steel would be likely to form in a fine dispersion due to the rapid solidification and cooling involved. Furthermore, during the brief temperature cycles involved in welding, steels with the finely dispersed manganese-sulphide inclusions would be more prone to conversion to iron sulphide than with larger agglomerations of sulphides.

In addition to the investigation at Rautaruukki Oy and ESAB AB, which arrived at findings completely opposed to Wranglen, Strommen(22) in 1975 also reported results that tend to disprove Wranglen's theory. Strommen investigated the effects of both:

- Rapid cooling in high-manganese steels;

- The effects of heating to 1,400°C (fusion-zone temperature) and slow cooling of a steel containing 0.024% sulphur.

Strommen identified the steel that had not been heat treated to 1,400°C as having, "active sulphides", while the steel that had been heat treated did not show active sulphides. Furthermore, he noted that microstructures indicative of higher cooling rates from the transformation temperatures were more susceptible to corrosion.

Although it is generally conceded that sulphide inclusions can initiate pitting attack, several investigators have argued against Wranglen's conclusions. These arguments have been documented by Adrian(20):

- Examinations by other investigators show that there were no iron sulphides present (the sulphide form argued by Wranglen to be harmful) in either the steel plate or the HAZ from the Kiev corroded specimen;

- Exposure of welded plates representing both casting techniques to the ESAB corrosion test failed to show any difference in the corrosion susceptibility;

- Investigations into the types of sulphides present in continuously cast and ingot-cast steels failed to show any difference in sulphides.

Other arguments against the "active-sulphide" role are:

- The fact that the investigators have found a post heat treatment of 500°C can decrease the corrosion susceptibility of weld joints;

- The fact that steels of very low sulphur contents are being used, and HAZ corrosion is still reported.

E. NORTHERN EUROPEAN PRACTISE

1. Plate Development

The investigative work by Relander, Rasanen, Saarinen, Valanti, and others resulted in the necessary groundwork for the development of a ship plate and of welding methods that would eliminate the HAZ corrosion that had been observed on the Kiev.

Numerous steel types were investigated at the steel works of Rautaruukki Oy in order to determine the most favorable ship-plate chemistry(23). Test methods consisted of the ESAB corrosion test using the OK48.23 welding electrode and the anodic dissolution test developed by Saarinen using artificially produced heat-affected zones.

(a) Alloy Levels

Results of the preliminary research indicated that the manganese content in high-strength fracture-tough steels was a major contributing factor to HAZ corrosion. The indications were that manganese levels needed to be reduced to about 1% to avoid HAZ corrosion. Raising the heat input during welding would also have beneficial effects; however, high welding-heat inputs tend to reduce HAZ fracture toughness. In addition, a substitute for manganese content would have to be found in order to maintain charpy impact requirements required by Lloyds EH Grades.

Further developmental research(23) showed the following effects of plate chemistry upon HAZ corrosion:

- Chromium and nickel tended to increase heat-affected zone corrosion;

- Between 0.10% and 0.18%, carbon did not appear to affect the corrosion rate;

- An increase in the silicon content of steel increased HAZ corrosion rate;

- The microalloying elements, vanadium and niobium, had no effect on corrosion rate.

i. Fusion-Line Corrosion

A second distinctly different type of corrosion adjacent to the weld seam was also observed(23). Occurrence of a fine line of corrosion directly along the fusion line was attributed to the constitutional liquidation of sulphides and the formation of continuous sulphide films on austenitic grain boundaries. In order to avoid fusion-line corrosion, cerium alloying was used to form high-melting oxysulphides, and the sulphur level was kept below 0.015%.

ii. Silicon Content

It was also found(23) that when used with steels containing about 0.2% to 0.3% coppper additions (apparently used to prevent excessive plate corrosion), the ESAB OK48.23 electrode could corrode. This was controlled by ensuring a minimum silicon content of 0.2% in the steel plate. The relationship of weld corrosion to silicon content is shown in Figure II-4.

(b) Polar Steels

When the plate chemistry for corrosion resistance was set, development of a steel that would meet the toughness requirements of Lloyds Grade EH could proceed. The developmental work is well summarized in the paper by Relander and Typi(24). Microalloying with vanadium and niobium was used to compensate for the loss in strength and toughness caused by the restricted manganese levels.

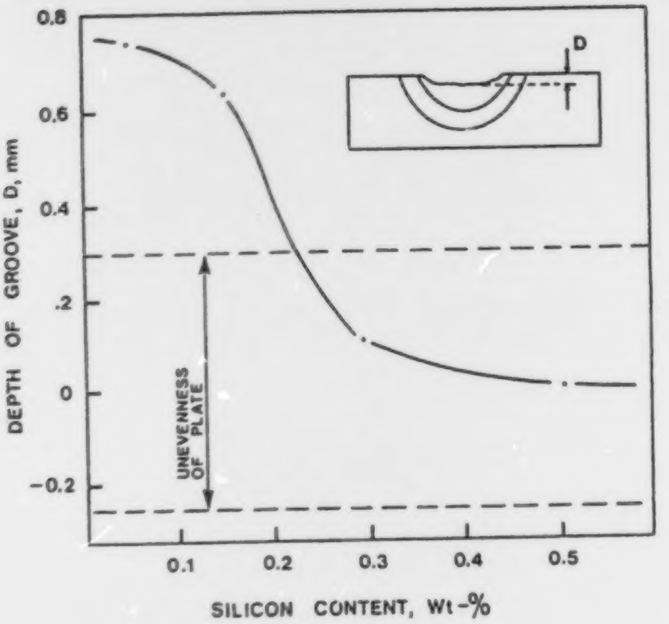


FIGURE II-4 - DEPTH OF CORROSION IN WELD METAL OK48.23 AS A FUNCTION OF SILICON CONTENT IN SHIP PLATE. FOUR MONTHS IN ESAB CORROSION TEST. SOURCE: RASANEN & RELANDER(23)

The resulting Polar steels were developed in parallel with the welding parameters necessary to avoid HAZ corrosion and to maintain high toughness.

Polar steels meeting Lloyds Grade EH32 are available in plate sizes up to and including 50 mm and steel meeting EH36 in plate sizes up to 20 mm(25). High reduction of area values in the transverse direction should give the plate good resistance to lamellar tearing.

Results of developmental testing for Raex 32 E Polar (meeting EH36 requirements) are shown in Table II-3.

Chemical composition limits are given in Table II-4. In practise, the manganese level is kept to about 1%.

2. Welding Practise

(a) Heat Input

Using the data of welding-heat input and preheat temperatures accumulated by Relander and others, data for the implementation of welding procedures was developed. The correlation between permissible minimum welding-heat input and thickness of Polar plate necessary to avoid the formation of corrosion-susceptible, heat-affected zones is shown in Figure II-5. The correlation takes into account welding preheat temperature and establishes a maximum heat-input level to maintain adequate resistance to brittle fracture. Rautaruukki Oy recommends that this correlation be followed in welding icebreaker hulls constructed of Polar steels.

According to Figure II-5, a minimum welding-heat input of 18 kJ/cm would be required for a 1-in plate. Using a standard formula for heat-input equivalent,

TABLE II-3

MECHANICAL PROPERTIES OF RAEX 32 E POLAR

PLATE THICKNESS (mm)	LOWER YIELD POINT (MPa)	ULTIMATE TENSILE STRENGTH (MPa)	PERCENT ELONGATION	PERCENT REDUCTION IN AREA	LONGITUDINAL CHARPY V-NOTCH -40°C (joules)	REDUCTION IN AREA SHORT-TRANSVERSE
12	372	526	32	72	53	36
20	342	501	34	71	96	48
30	346	500	37	73	118	65
50	346	499	36	74	98	61

TABLE II-4

COMPOSITION LIMITS OF RAEX 32 E POLAR

ELEMENT	WEIGHT PERCENT
Carbon	0.18 max.
Silicon	0.20 - 0.35
Manganese	1.10 max.
Aluminum	0.020 min.
Copper	0.30
Niobium	0.03
Vanadium	0.08
Sulphur	0.010 max.
Cerium	0.02 - 0.06
Ce/s	greater than 1.4

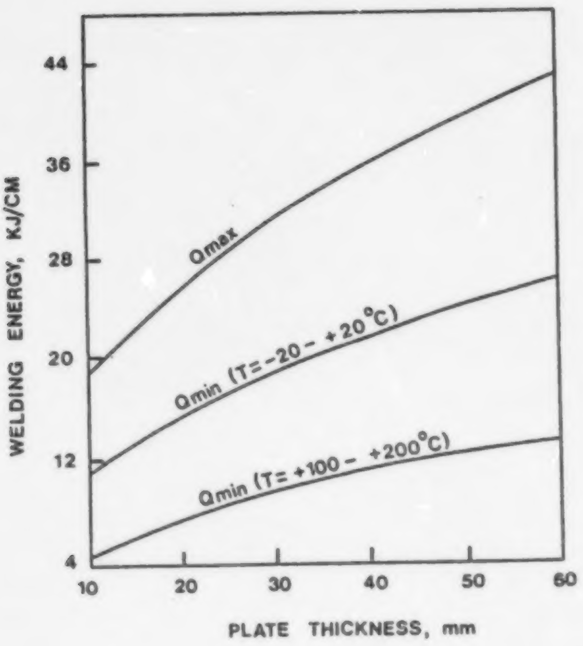


FIGURE II-5 - RECOMMENDED WELDING HEAT INPUT FOR POLAR SHIP PLATES.
SOURCE: RASANEN AND RELANDER(23)

$$Hnet = \frac{fEI}{V} \times 60$$

where Hnet = heat input, J/cm
f = heat transfer efficiency, 0.9
E = arc voltage, v
I = welding current, amps
V = travel speed, cm/min

it can be seen that the heat inputs recommended are in line with standard welding practise. Consider a horizontal joint which would be typical for shipyard conditions welded as per the following typical parameters:

- Electrode size, 5 mm on cover pass;
- Current, 210 amps;
- Arc voltage, 25 volts;
- Travel speed, 16.5 cm/min.

Heat input under these conditions would be 17 kJ/cm. On larger plates (requiring higher minimum heat inputs), heat input could be increased by reducing travel speed slightly. Heat input on vertical up-welding would be higher because of reduced travel speeds.

(b) Welding Consumables

i. Shielded Metal-Arc Process

The present designation of the ESAB corrosion-resistant electrode for manual welding is OK73.08, classified by A.W.S. under A5.5-81: E8018G. It is approved by Lloyds Register, Det Norske Veritas, and American Bureau of Shipping. A chemical analysis is shown in Table II-5 and mechanical properties in Table II-6.

Corrosion of the weld metal has occasionally been reported with Rautaruukki Polar plate that approaches the lower limit of allowable silicon and the upper limit of allowable copper(13). The electrode OK73.68 (2.5% nickel) has reportedly given better results. This electrode also has the additional advantage of having good impact properties down to -60°C. Electrode classification is A.W.S. A5.5-81: E8018-C1. The electrode is approved by the three major ship-classification societies.

Mechanical properties are shown in Table II-7.

ii. Submerged Arc and Flux-Core Process

Consumables for SAW and FCAW are supplied by ESAB which give a deposited weld-metal composition similar to OK73.68. These are:

SAW	FCAW
- OK Autrod 13.27 With OK Flux 10.62	- OK Tubrod 14.04
- Good Impact Properties	- OK Tubrod 15.25
	- Good impact properties to -60°C

3. Operating History

Rautaruukki Oy reports that inspection visits to shipyards engaged in fabrication found problems in controlling

TABLE II-5

ESAB OK73.08

TYPICAL WELD METAL ANALYSIS

ELEMENT	WEIGHT PERCENT
Carbon	0.06
Silicon	0.40
Manganese	1.00
Nickel	0.60
Copper	0.40

TABLE II-6

ESAB OK73.08

TYPICAL MECHANICAL PROPERTIES - WELD METAL

Ultimate Tensile Strength (MPa)	590
Yield Strength (MPa)	490
Elongation (%)	28
Charpy V-Impact Properties (joules at -40°C)	70

TABLE II-7

ESAB OK 73.68

TYPICAL MECHANICAL PROPERTIES - WELD METAL

Ultimate Tensile Strength (MPa)	600
Yield Strength (MPa)	500
Elongation (%)	25
Charpy V-Impact Properties (joules at -40°C)	70

the heat-input levels actually used. Observation of welding operations showed that at times heat inputs of 10 kJ/cm were occurring when the minimum recommended heat input was 20 kJ/cm.

Inspection of icebreakers after a few years of service also revealed isolated instances of HAZ corrosion.

F. CANADIAN PRACTICE

1. Introduction

Icegoing vessels in Canada are designed and built to meet the specifications of one of the major ship-classification societies, of which Lloyds, American Bureau of Shipping, and Det Norske Veritas are the most common. In addition, the requirements of Canadian Arctic Shipping Pollution Prevention Regulations (CASPPR) are observed. These specifications do not yet directly address weld corrosion, although recognition of the problem is emerging. Det Norske Veritas is currently investigating the subject and may address weld-area corrosion in future specifications(27).

Designers can, of course, augment or improve on the rules to obtain the desired strength, longevity, and operational characteristics. BeauDril, for instance, built certain sections of the hull on their vessels, "Terry Fox" and "Kalvik", with a steel that required a lower charpy V-notch transition temperataure than the EH36 Grade. So-called EH36 modified was ordered requiring 34 J impact strength at -60°C.

2. Summary of Rules

The pertinent areas of the ship-classification societies' most recently available rules are summarized. The three major societies generally specify similar material types and designations.

(a) Steels - Lloyds Registry of Shipping (1985)

Chemical and mechanical property requirements for normal and high-strength steels are shown in Tables II-8, 9, 10, and 11. These are similar to the steel grades and requirements of A.B.S. and D.N.V.

These tables are not reproduced in their entirety and are presented for information only.

(b) Welding

Weldments are required to meet the mechanical properties of the specified steel plate. Acceptable electrodes for different steel classes, special requirements for certain processes, welding sequence, preheat, and post-heat-treatment requirements are also covered by the specifications, but for the most part, the methods of attaining the desired weld-zone mechanical properties are left to the discretion of the fabricator. With the exception of general requirements relative to the formulation and implementation of welding procedures, the classification societies concern themselves primarily with rules for qualification of procedures, welding operators, and welding consumables. Quality control of finished weldments is also a concern and is covered under the rules in the sections dealing with structural design. Particulars of each classification society's rules are dealt with in the following sections.

TABLE II-8

CHEMICAL REQUIREMENTS AND DEOXIDATION PRACTICE FOR NORMAL-STRENGTH STEELS

	GRADE			
	A	B	D	E
Deoxidation	any method	any method except rimmed steel	Killed,	Killed and fine grain treated with aluminum
Chemical Composition, %				
Carbon	0.23 max.	0.21 max.	0.21 max.	0.18 max.
Manganese		0.80 min.	0.60 min.	0.70 min.
Silicon	0.50 max.	0.50 max.	0.10-0.50	0.10-0.50
Sulphur	0.040 max.	0.040 max.	0.040 max.	0.040 max.
Phosphorous	0.040 max.	0.040 max.	0.040 max.	0.040 max.
Aluminum (acid soluble)	---	---	---	0.015 min.
Carbon + 1/3 of the manganese content is not to exceed 0.40%.				

*Taken from Lloyds Registry of Shipping (1985) Rules for the Manufacture, Testing, and Certification of Materials.

TABLE II-9

MECHANICAL PROPERTY REQUIREMENTS
FOR NORMAL-STRENGTH STEELS

	GRADE			
	A	B	D	E
Yield Stress, N/mm^2 minimum	235	235	235	235
Tensile Strength, N/mm^2	400-490	400-490	400-490	400-490
Elongation on 5.65 S_o, % minimum	22	22	22	22
Charpy V-Notch Impact Tests (longitudinal)				
Test Temperature, °C	---	0	-10	-40
Average Energy, J minimum	---	27	27	27

Note: S_o = Area of test specimen.

*Taken from Lloyds Registry of Shipping (1985) Rules for the Manufacture, Testing, and Certification of Materials.

TABLE II-10

CHEMICAL REQUIREMENTS AND DEOXIDATION

PRACTICE FOR HIGHER-STRENGTH STEELS

	GRADE								
	AH32	DH32	EH32	AH34S	DH34S	EH34S	AH36	DH36	EH36
Deoxidation	killed or semi-killed	killed	killed	killed or semi-killed	killed	killed	killed or semi-killed	killed	killed
Chemical Composition, %									
Carbon	0.18 max								
Manganese	0.90 - 1.60								
Silicon	0.10 - 0.50								
Sulphur	0.040 max								
Phosphorous	0.040 max								
Grain Refining Elements									
Aluminum (acid soluble)	0.015 min			0.015 min			0.015 min		
Niobium	---			0.015 - 0.05			0.015 - 0.05		
Vanadium	---			0.03 - 0.10			0.05 - 0.10		
Residual Elements									
Copper	0.35 max								
Chromium	0.20 max								
Nickel	0.40 max								
Molybdenum	0.08 max								

*Taken from Lloyds Registry of Shipping (1985) Rules for the Manufacture, Testing, and Certification of Materials.

TABLE II-11

MECHANICAL PROPERTY REQUIREMENTS

FOR HIGHER STRENGTH STEELS

	GRADE								
	AH32	DH32	EH32	AH34S	DH34S	EH34S	AH36	DH36	EH36
Yield Stress, N/mm^2 minimum	315	315	315	340	340	340	355	355	355
Tensile Strength, N/mm^2	440-590	440-590	440-590	450-610	450-610	450-610	490-620	490-620	490-620
Elongation on 5.65 S_o, % minimum	22	22	22	22	22	22	21	21	21
Charpy V-Notch Impact Tests (longitudinal)									
Test Temperature, °C	0	-20	-40	0	-20	-40	0	-20	-40
Average Energy, J minimum	31	31	31	34	34	34	34	34	34

Note: S_o = Cross-sectional area of test specimen.

*Taken from Lloyds Registry of Shipping (1985) Rules for the Manufacture, Testing, and Certification of Materials.

i. Det Norske Veritas (July 1983)

Chemical Analysis

The chemical analysis of the weld metal made by the electrodes is supplied by the manufacturer.

Electrode Designation

Electrodes are divided into Grades 1, 2, and 3 for normal-strength steels (400 to 490 MPa U.T.S.) and 2Y and 3Y for high-strength steels. Electrodes for high-strength steels are to be hydrogen tested. Mechanical property requirements for deposited weld metal are shown in Table II-12.

ii. Lloyds Registry of Shipping (1985)

Electrode Designations

For normal strength steels:

Grade 3 - For welding any combination of grades;

Grade 2 - For welding any combination of steels other than Grade E to Grade E;

Grade 1 - For welding Grade A to any other grade.

TABLE II-12

MECHANICAL PROPERTY REQUIREMENTS FOR DET NORSKE VERITAS ELECTRODE CLASSIFICATION

ELECTRODE DESIGNATION	UPPER YIELD POINT, MIN (MPa)	TENSILE STRENGTH (MPa)	MINIMUM PERCENT ELONGATION (in 50 mm)	CHARPY V-NOTCH, MIN (joules)
1	305	400-560	22	47 @ +20°C
2	305	400-560	22	47 @ 0°C
3	305	400-560	22	47 @ -20°C or 61 @ -10°C
2Y	375	490-660	22	47 @ 0°C
3Y	375	490-660	22	47 @ -20°C

For higher tensile steels:

Grade 3Y - For welding any combination of grades;

Grade 2Y - For welding any combination of grades other than Grade EH to Grade EH;

Grade 1Y - For welding Grade AH to any other grade.

Mechanical property requirements for electrodes are, for the most part, similar to Det Norske Veritas.

Welding of Higher Tensile Steel

The following guidelines are used in the determination of preheat.

Carbon Equivalent	Procedure
Greater than 0.45%.	Preheat and low-hydrogen electrodes mandatory.
Greater than 0.41%, less than 0.45%.	Low-hydrogen electrodes required.
Less than 0.41%.	Low-hydrogen electrodes and/or preheating not required.

iii. American Bureau of Shipping (1981)

Filler metals are to be of a type suitable to produce sound welds that have strength and toughness comparable to the materials being welded. The Bureau maintains a separately issued list of approved filler metals entitled, "Approved Welding Electrodes, Wire-Flux, and Wire-Gas Combinations". This list indicates the grade and general applications for which such filler metals may be employed.

G. CANADIAN EXPERIENCE AND CASE HISTORIES

1. General

Canadian icegoing vessels have shown instances of severe weld corrosion over the years. Vessels have been manufactured primarily using E7018 and E6011 electrodes, and hence, the weld corrosion observed is not surprising.

In 1967, Campbell(9)made a thorough investigation of samples from the "Sir Humphrey Gilbert" and suggested that better results might be obtained by using a nickel-alloyed electrode. Since no satisfactory method had been developed at that time for controlling corrosion of the hull as a whole, it was concluded that the application of improved coatings and cathodic protection warranted more immediate attention.

Corrosion of the heat-affected zone has not been reported on Coast Guard vessels. The higher manganese EH36 steels are not yet in use on Coast Guard vessels, and therefore, according to the Scandinavian investigations, corrosion should not to be expected.

Heat-affected zone corrosion has been reported recently on private-industry vessels that have been launched since 1979. These vessels have been constructed using the higher manganese steels.

2. Case Histories

(a) Canmar M.V. Kigoriak - Corrosion Evaluation

The Kigoriak was built at Saint John Shipbuilding and Dry Dock in 1979 to Lloyds' rules. The vessel is classified as an Arctic Class 3, Lloyds 100 Al Icebreaker. The steel plate consisted of Lloyds Grade EH36 and Grade E. The consumables were E7018.

The vessel was launched without a coating or total cathodic-protection system in place. The performance of the weld seams can, therefore, be judged without considering these two major variables. The vessel operated in this "bare-hull" condition until August 1982, at which time, an Inerta 160 coating system augmented by a cathodic-protection system was installed.

i. Dry-Dock Inspection - December 1981

The first dry-dock inspection was conducted at McKinley Bay after two summers of operation in the Beaufort Sea. Results of this inspection indicated that, as expected, the hull plating was corroding significantly (described as pitting in the inspection report), with the depth of metal loss estimated to be 1 mm to 2 mm throughout the hull. Excessive weld corrosion was occurring, with metal loss much greater than that observed on the parent plate. Depths of weld corrosion reported variedly from 5 mm to 7 mm in the rudder, stern area, and midships, to "70% of the weld" in the bottom plates of the forward section.

The presence of corrosion in the heat-affected zone is mentioned in the inspection report, but is not described in detail.

It is interesting to note that in the stern area of the vessel, where zinc sacrificial anodes had been fitted, no corrosion of the parent plate or weld seams had taken place.

ii. Dry-Dock Inspection - June 1982

Weld-zone corrosion encompassing weld and heat-affected zone was described as being severe. As Campbell reported from his examination of C.C.G.S. "Sir Humphrey Gilbert", the weld corrosion appeared to follow the lines of the original weld beads or the capping pass.

The extent of the weld corrosion is put into perspective by the estimate made for the required weld repair work. It was estimated that 5,000 ft of weld required repair, a task which would require about 3,000 man-hours to gouge and reweld.

iii. Metallurgical Analysis of Corrosion Specimens

A sample of 35-mm thick hull plate from the bow area of the Kigoriak has been examined. The sample was removed from the vessel after the 1981 operating season and, so, represents two seasons of icebreaking operation. In the area where this sample was removed, the hull had never been coated or protected by sacrificial anodes. The sample provides an example of weld corrosion unaffected by unrelated factors.

Photographs II-1, 2, and 3 clearly show the large degree of corrosion damage on both the hull plate and the weld metal. The weld zone has undergone an even greater degree of attack than the parent plate, as evidenced by:

- The almost complete dissolution of the weld cap, and;
- The two corrosion grooves at the extremities of the weld metal, in which corrosion has penetrated 2 mm to 3 mm below the level of the parent plate and 1 mm below levels of adjacent corrosion on the weld metal.

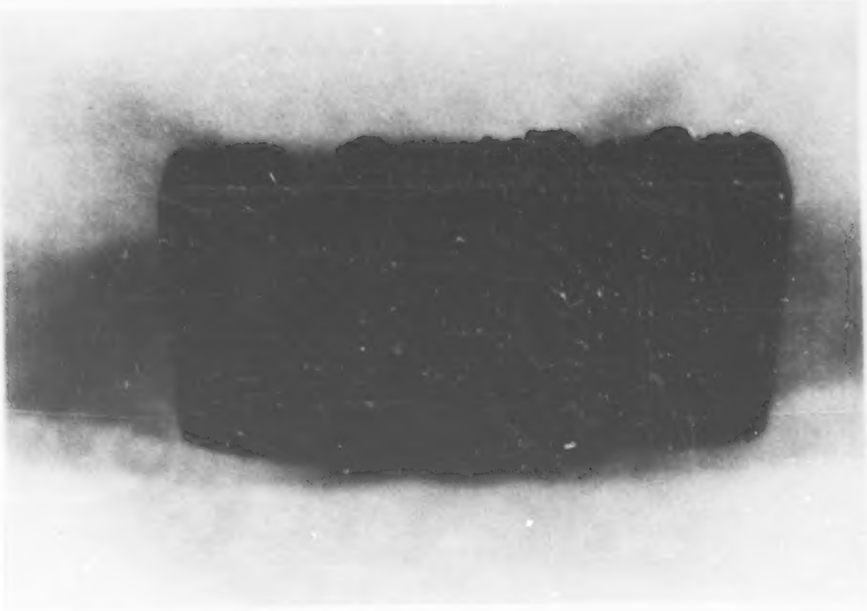
Photographs II-2 and 3, which clearly illustrate the abrupt transition between the weld area and the adjacent corrosion grooves, indicate the grooves are the result of corrosion in the heat-affected zone.

Microstructural Examination

The microstructures at the base of the HAZ corrosion and adjacent to the capping base on the back side weld were clearly bainitic, probably of the lower bainite type. No martensite was observed in heat-affected zones. Representative micrographs are shown in Photographs II-4 and 5.

PHOTOGRAPH II-1 - SHOWING SURFACE OF HULL PLATE FROM KIGORIAK AT WELD JOINT

PHOTOGRAPH II-2 - SHOWING ACID-ETCHED CROSS-SECTION OF HULL WELD
FROM KIGORIAK
NOTE PREFERRED CORROSION AT EDGES OF WELD



PHOTOGRAPH II-3 - SHOWING ACID-ETCHED CROSS-SECTION OF HULL WELD
FROM KIGORIAK
NOTE PREFERRED CORROSION AT EDGES OF WELD

PHOTOGRAPH II-4 - MICROSTRUCTURE AT BASE OF CORROSION GROOVE IN HEAT-AFFECTED ZONE
- 600X MAGNIFICATION
- NITAL ETCH

PHOTOGRAPH II-5 - MICROSTRUCTURE IN HEAT-AFFECTED ZONE ON BACK SIDE OF PLATE
- 600X MAGNIFICATION
- NITAL ETCH

Steel Plate and Weld Metal Analysis

The steel plate was reported to be EH36, which was verified by chemical analysis, tensile test, and charpy impact tests. Results are shown in Tables II-13 and 14, respectively. The welding electrode was reported to be an E7018. The weld-metal analysis, also shown in Table II-13, is in agreement with this classification.

According to the graphs of heat input versus manganese content (shown in Figure II-5), heat input of approximately 24 kJ/cm would be necessary to avoid HAZ corrosion at the manganese level of 1.45%. Referring to the example shown on Page II-30, this level of heat input could be considered on the high side.

(b) Canmar Supplier - Metallurgical Analysis of Corrosion Specimens

Unfortunately, no historical information is available for the sample examined.

Plate thickness is 22 mm and steel type is LLoyds Grade E, which was verified by a manganese analysis showing 1.0%. The welding electrode is E7018. Therefore, according to data for Rautauruukki Oy, HAZ corrosion should not be a problem.

Photograph II-6 illustrates a complete lack of protective coating, yet very little corrosion damage to the plate can be seen. The weld cap has corroded, but the depth of penetration is not below the plate surface. There is also an indication of corrosion on one side of

TABLE II-13

PLATE AND WELD-METAL COMPOSITION (%)
FROM CORRODED WELD JOINT

M.V. KIGORIAK

ELEMENT	LLOYDS EH36	PLATE	WELD METAL	E7018 ELECTRODE (std comp)
Carbon	0.18 max.	0.162	0.06	0.08
Manganese	0.90-1.60	1.45	1.02	1.0
Silicon	0.10-0.50	0.34	0.54	0.5
Sulphur	0.04 max.	0.028	0.01	---
Phosphorous	0.04 max.	0.014	0.01	---
Nickel	0.04 max.	0	0.02	---
Chromium	0.25 max.	0.047	0.08	---
Copper	0.35 max.	0.026	0.05	---

TABLE II-14

MECHANICAL PROPERTIES

PLATE SAMPLE AT BOW AREA

M.V. KIGORIAK

	PLATE SAMPLE	LLOYDS EH36
Ultimate Tensile Strength (MPa)	539	490 - 620
Yield Strength (MPa)	370	350 min.
Percent Elongation (in 50 mm)	34	22
Reduction in Area (%)	71	---
Longitudinal Charpy V-Notch (joules @ -40°C)	78	34

the HAZ. Photograph II-7 also demonstrates a very small amount of metal loss along the fusion line.

Microstructures are shown in Photographs II-8 and 9. The heat-affected-zone microstructure can be classified as lower bainite, ferrite, and pearlite. The sharp corrosion groove in Photograph II-9 illustrates a slight, but decidedly preferential corrosion occurring along the fusion line.

(c) Canmar Explorer II

i. General Description

The Explorer II is a marine drill ship which was converted from a 1945 general cargo vessel in 1975. During this conversion, considerable steel work was replaced. Sponsons were added in 1975 and again in 1980 to improve vessel stability.

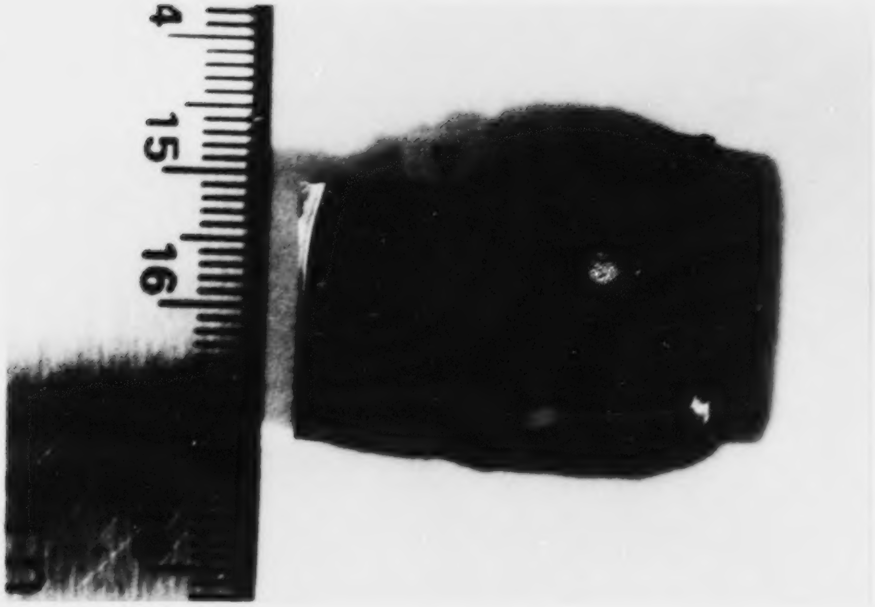
The hull now meets ABS Ice-Reinforced Type A1 Super Class 1AA.

An aluminum sacrificial anode cathodic protection system was fitted in 1975. The anodes were fitted on the bottom and on side shell plating. A standard marine coating was also applied. Neither the sacrificial anode system nor the coating system had been repaired since 1975.

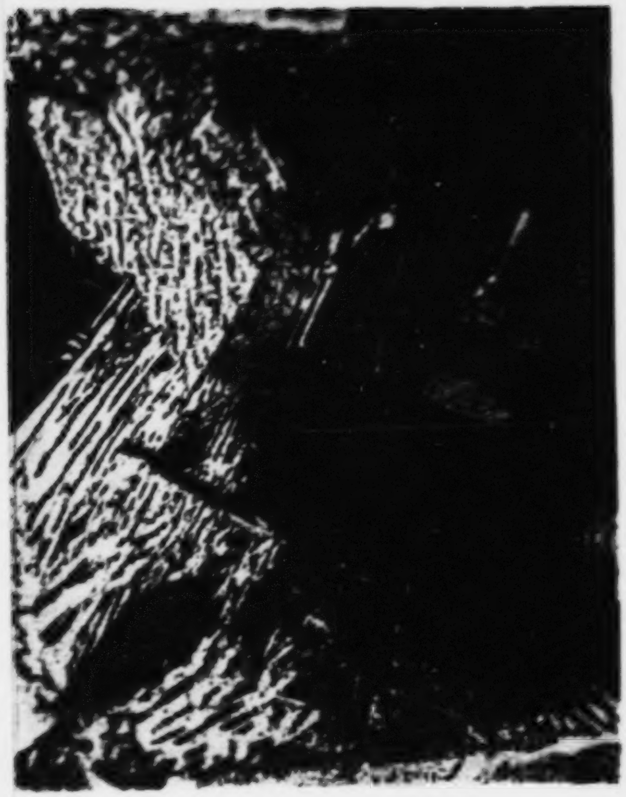
ii. Dry-Dock Inspection - November 1983

On the parent plate, general, fairly shallow pitting was observed. This seems to be fairly typical of vessels operating in ice conditions. The corrosion was reported to be much more pronounced in the weld metal and heat affected

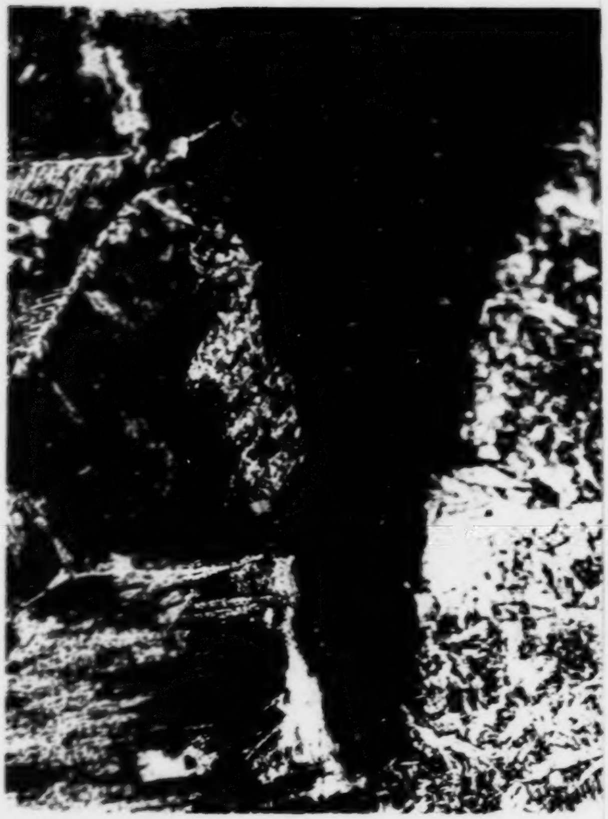
PHOTOGRAPH II-6 - SHOWING HULL PLATE AT WELD JOINT FROM CANMAR SUPPLIER



PHOTOGRAPH II-7 - SHOWING ACID-ETCHED CROSS-SECTION AT WELD JOINT
FROM CANMAR SUPPLIER
NOTE SHARP CORROSION GROOVE AT FUSION LINE



PHOTOGRAPH II-8 - MICROSTRUCTURE IN HEAT-AFFECTED ZONE, CANMAR
SUPPLIER
- 600X MAGNIFICATION
- NITAL ETCH


HEAT
AFFECTED
ZONE
WELD
METAL

PHOTOGRAPH II-9 - MICROGRAPH SHOWING SHARP CORROSION GROOVE ALONG FUSION LINE
- 260X MAGNIFICATION
- NITAL ETCH

zones at the stern and bow areas. The HAZ corrosion was described as undercutting. In one location corrosion of the weld seams to a depth of 10 mm and "undercutting" of the weld seams to a depth of 7 mm was reported.

(d) BeauDril Vessels

i. General

BeauDril is the Beaufort offshore drilling arm of Gulf Canada Resources Inc. In the summer of 1983, Beaudrill launched two Arctic Class 4 Icebreakers, the "M.V. Kalvik" and the "M.V. Terry Fox". Both vessels were built in the shipyards of Burrard Yarrows Corporation (now known as Versatile Pacific Shipyards Inc.). The vessels as-launched were provided with Inerta 160 abrasion-resistant coating and an impressed-current cathodic-protection system.

Information is presented here on the welding parameters and hull plate employed in the fabrication of the "M.V. Terry Fox". With respect to weld-zone corrosion, no special precautions were taken in specifying steel plate or welding materials and procedures. Metallurgy of both steel plate and weld zones was specified with high fracture toughness of foremost importance. In this respect, the Terry Fox and the Kalvik represented the leading edge at the time of manufacture in Canadian icebreaker fabrication.

ii. Steel Plate

The majority of the hull was fabricated using a steel meeting a modified version of Lloyds EH36 specification, so-called EH36-Mod. Charpy V-notch specifications were enhanced to require 34 J at -60°C (usually -40°C). The bottom portion of the hull amidships only was specified as Lloyds Grade E material.

The EH36-Mod steel was manufactured in a basic oxygen furnace, was fully killed, and made to fine-grain practice. To obtain very good impact properties and through thickness ductility, sulphur was restricted to a maximum of 0.01%. Sulphur contents in the as-received plate were in the 0.001% to 0.0015% range. All plate was given a standard normalizing treatment or rolled using Nippon Steel's "intercritical rolling process".

The chemical analysis specification of the EH36-Mod is shown in Table II-15 with a representative analysis of the as-delivered plate. In order to avoid using a welding preheat during fabrication, the carbon equivalent was restricted to a maximum of 0 41%.

Physical property specifications are shown in Table II-16.

The difference between Grade E steels and the EH36 grades are as follows:

- A manganese limit of 1.35% in Grade E as compared to 1.6% in the EH36;

TABLE II-15

M.V. "TERRY FOX"

CHEMICAL REQUIREMENTS OF PLATE SPECIFICATIONS

(all values as weight %)

	EH36-MOD* REQUIREMENTS	EH36-MOD AS-RECEIVED	LLOYDS & ABS* EH36 REQUIREMENTS	LLOYDS & ABS* "E" REQUIREMENTS
Carbon	0.15	0.09	0.18	0.18
Silicon	0.10 - 0.35	0.24	0.10 - 0.50	0.10 - 0.35
Manganese	0.70 - 1.6	1.60	0.90 - 1.60	0.70 - 1.35
Phosphorus	0.04	0.013	0.04	0.04
Sulphur	0.01	0.001	0.04	0.04
Copper	0.35	0.27	0.35	-
Nickel	0.80	0.27	0.40	-
Chromium	0.20	0.05	0.25	-
Molybdenum	0.08	0	0.08	-
Vanadium	0.10	0	0.10	-
Niobium	0.05	0.05	0.05	-

*Maximum levels, unless range is given.

TABLE II-16

"M V TERRY FOX"

MECHANICAL-PROPERTY REQUIREMENTS OF STEEL PLATE

	EH36-MOD REQUIREMENTS	EH36-MOD AS-RECEIVED	LLOYDS & ABS EH36 REQUIREMENTS	LLOYDS & ABS "E" REQUIREMENTS
Ultimate Tensile Strenth (MPa)	490 - 620	541	490 - 620	400 - 552
Yield Strength (MPa)	350	466	350	235
Percent Elongation (in 2 inches)	22	34	22	34
CVN Impact Energy (Joules)	34 @ -60°C	112 @ -60°C	34 @ -40°C	27 @ -40°C

- Ultimate tensile strength and yield strength at 400 MPa and 235 MPa, respectively, in Grade E, compared with 490 MPa and 350 MPa in EH36.

iii. Welding

EH36 Modified Steel

- FCAW and SMAW Processes

Flux-core semiautomatic welding (FCAW) and manual-shielded metal-arc welding (SMAW), were used in the majority of the seams at the icebreaking bow of the Gulf ships manufactured at Burrard Yarrows, the hull portion which will see the most ice abrasion.

Most of the manual welding of the EH36 modified steel used an E8018-C1 class of electrode. The electrodes used under this classification were produced by Atom Arc of Chemetron Corporation. The Atom Arc E8018-C1 is a 2.5% nickel electrode with the following composition:

- C : 0.04%;
- Ni: 2.37%;
- P : 0.02%;
- S : 0.02%;
- Mn: 1.06%;
- Si: 0.31%.

Semiautomatic welding used Dual Shield 11 80 Ni-1, manufactured by Chemetron

Corporation. A shielding gas mixture of 75% argon and 25% CO_2 is specified by the manufacturer and was used in fabrication. Manufacturer's data shows the typical undiluted weld metal analysis tabulated below:

- C : 0.05%;
- Mn: 1.46%;
- Si: 0.40%;
- P : 0.02%;
- S : 0.01%;
- Ni: 0.95%.

Welding-heat inputs for both flux-cored arc welding and shielded-metal arc welding were tightly controlled with regard to a maximum heat input. This was done to ensure good charpy properties, since high heat inputs generally result in lower impact energy as was discussed previously. Table II-17 shows charpy impact test results for weld qualification tests on EH36 modified steel.

The heat-input values shown in Table II-17 are the maximum allowable. The actual values fell to as low as 15 KJ/cm for FCAW processes. Weld metal was deposited in stringer beads with a slight weave being incorporated on capping passes rather than a full weave. Welding in this manner controls heat input and provides maximum grain refinement to previously deposited weld metal and heat-affected zones.

TABLE II-17

SUMMARY OF IMPACT RESULTS

PROCEDURE QUALIFICATION TESTS

		IMPACT ENERGY (Average ft lbs @ -60°C) DEEP VEE SIDE OF WELD		
		WELD	FUSION LINE	HAZ 3 mm FROM F.L.
FCAW	Vertical Weld *22 KJ/cm	41	100	90
	Horizontal Weld *22 KJ/cm	34	92	210
SMAW	Vertical Welds *29 KJ/cm	36	71	202
	Horizontal Welds *27 KJ/cm	53	91	212
	Overhead Welds *27 KJ/cm	47	124	194

*Maximum heat inputs.

- Submerged Arc (SAW) Welding

Submerged arc welding was used only on welds for the sides of the ship where welding was done out of place in the flat position. The welding wire and flux used was manufactured by Nippon Steel Welding Products and Engineering Co. Ltd. Multipass welding (32 kJ/cm heat input) was used, although the wire-flux combination could be used for one-pass (high heat input) welding in a limited thickness range. Chemical analysis of the welding wire and a typical (supplier documented) as-deposited weld analysis is shown in Table II-18.

Grade E Steel

Butt joints in the Grade E plate and joints involving Grade E to EH36 modified plate were made using E7018-Class electrodes for the SMAW processes and Linde FC 707 with CO_2 shielding gas for FCAW. Both of these processes are low hydrogen with a low-carbon weld deposit.

Submerged arc welding was carried out using Lincoln L-61 wire and 860 flux.

iv. Grinding of Welds

Manual and semiautomatic welds were ground approximately 1/16 inch to give them a uniform profile. The welds were not ground flush with the base metal, nor were they ground far enough to

TABLE II-18

CHEMICAL ANALYSIS OF NITTETSU WELD DEPOSITS

(wt%)

ELEMENT	NITTETSU WELDING WIRE	NITTETSU WELDING WIRE AS-DEPOSITED
Carbon	0.10	0.08
Silicon	0.10	0.23
Manganese	2.55	1.42
Phosphorus	0.012	0.012
Sulphur	0.006	0.009

remove the grooves between adjacent weld beads.

Submerged arc welds were not ground.

v. Weld Inspection

Weld inspection consisted of 150 spot-check radiographs.

vi. Comments on Welding Metallurgy of BeauDril Vessels

Heat-Affected Zone

The welding-heat inputs for SMAW and FCAW processes on EH36 modified plate used by Burrard Yarrows Corporation have been compared with the permissible welding energy diagram shown in Figure II-5. The median welding energies used by Burrard Yarrows Corporation fall above the $Q_{minimum}$ welding energy for Polar ship plate welded without preheat. The minimum welding energies used of 15 KJ/cm fall somewhat below the $Q_{minimum}$ line. The $Q_{minimum}$ line predicts the minimum welding energy which must be used on Polar ship plate to prevent the formation of low-temperature transformation products in the heat-affected zone, thereby guarding against corrosion susceptibility.

The Nippon Steel EH36 modified steel has a much higher manganese content (0.5% more Mn) than the Polar steel. High manganese content is thought to increase the percentage of low-temperature transformation products formed in the HAZ which results in increased HAZ corrosion. In addition, the EH36 plate contains a significant amount (0.26%) of nickel which also promotes the formation of low-temperature transformation products. The Q-minimum line for the EH36 will be higher than for Polar steel. Therefore, a significant corrosion rate in the heat-affected zone of the EH36 welds made by FCAW and SMAW processes is a possibility when the minimum welding-heat inputs used by Burrard Yarrows are in effect.

Fusion Line

Fusion-line corrosion is not expected because of the very low sulphur contents in the as-delivered EH36 plate.

Weld Metal

Corrosion on the weld metal is not expected in the SMAW welds where the 8018-C1 electrodes were used. Weld-metal corrosion is a distinct possibility on the welds made with the automatic and semiautomatic processes.

vii. Performance of the M.V. Terry Fox

The Terry Fox has now been in operation for two drilling seasons. A dry-docking took place in October 1985.

Extensive coating damage had occurred, and HAZ corrosion was reported in areas of the bow. The extent of corrosion damage was not considered severe enough to warrant repair.

It was also reported that no significant weld corrosion had occurred.

BeauDril has encountered HAZ corrosion in other vessels in its Arctic fleet, and in some cases, repairs by gouging and rewelding have been carried out.

It is significant that the cathodic protection system had not protected those areas of the hull where the coating was removed.

H. STEELS FOR HIGH HEAT-INPUT WELDING

Nippon Steel Corporation(28) has developed steels which can be welded in very heavy sections using high welding-heat inputs while still maintaining good toughness at low temperatures in the heat-affected zone. The steels have been developed for the purpose of single-pass, submerged arc welding which greatly speeds production. Insofar as the limitations of the processes permit, it is likely the steel could also be used for higher heat-input welding using SMAW and FCAW. If data developed by Rautaruukki Oy is correct, better HAZ corrosion resistance would be achieved.

The steel reported on is called HT50S (50 kg/mm^2 tensile strength) and meets the physical and chemical requirements of ABS EH36. Normally, high-heat-input welding results in lower HAZ toughness. This is due to the development of a coarse-grained structure in the heat-affected zone. In HT50S, fine TiN percipitates inhibit the grain-coarsening affect by pinning grain boundaries.

The Ship Structure Committee(29) has also been investigating the use of steels for high-heat-input welding. In this report, they examined the weld and heat-affected-zone properties of eight experimental steels along with three commercial steels. One of the experimental steels and two of the commercial steels would meet the physical requirements of EH36, although barely exceeding strength requirements. A further seven of the laboratory steels meet the requirements of Grade E.

When welded using a heat input of 30 kJ/cm, the steels meeting the EH36 Standard showed excellent impact energy absorportion in the HAZ at -40°C. Good resuls were also obtained at 70 kJ/cm. The two commercial steels were a calcium-treated ABS V-051 steel produced by Lukens Steel Company and a Nippon Steel HT-505, Class D, both supplied in the normalized condition.

III. COATINGS

A. USE OF COATINGS ON SHIPS

1. Summary of Findings

It is appropriate to summarize the findings of the investigation of coating use on ice-going vessels prior to presenting the detailed information obtained during the study. It is considered to be essential to emphasize the role and requirements of the coating process so that subsequent presentation of material can be better appreciated.

(a) High performance coatings can achieve substantial improvements in icebreaking performance and economy and very significant reductions in costs of corrosion damage in weld areas and elsewhere. It is unrewarding to apply any but the best possible coatings, proven by actual performance on ships.

(b) High performance coatings require a major investment in materials, facilities, personnel training and drydock time.

(c) The investment is at high risk, which is alleviated only by first class quality control procedures supported by solid contractual arrangements which clearly designate financial responsibility for any departure from established procedures.

(d) Any coatings will be damaged by abrasion from ice, with principal loss of coverage occurring in the bow area and along the waterline. It is implicit that such loss of coverage be minimized by using a high performance coating properly applied. Also, since coatings will be damaged, cathodic protection must be applied to control corrosion on bare metal and to prevent underfilm corrosion of coated area.

(e) The successful use of high performance coatings on ice-going vessels has been demonstrated, but the success has always been contingent on rigorous control of coating applicaton procedures.

2. General Requirements and Systems for Coating Ships Hulls

(a) Reduction of Hull Friction, Primarily for Ice-Free Waters

Ship hulls are coated to prevent metal corrosion and fouling by marine growths. A corroded and fouled hull will significantly increase the frictional resistance of the hull. This, in turn, increases the power required to maintain a certain speed with a consequent increase in fuel consumption. It has been reported in the literature that a Very Large Crude Carrier (VLCC) operating at a speed of 13 knots consumed more than $700,000 in extra fuel during a 30-month dry-dock cycle because of hull corrosion and fouling(30). A typical 250,000 dwt tanker that is freshly coated will run at 13 knots, with an output of 14,500 shaft horsepower (shp). Thirty months later, fouling and corrosion will have increased the power required to maintain the speed to 21,000 shp. This represents an increase of almost 30%. This problem can be minimized by shortening the dry-dock cycle, by performing interim hull maintenance, such as underwater cleaning, and by applying a better coating system to control corrosion and fouling.

The application of a good coating system to a hull is economical if it reduces fuel consumption, lengthens the dry-dock cycle, and reduces the maintenance required to renew welds or replace steel that is corroded. Ship owners must compare the cost of the coating system to the cost savings produced by using the improved coating.

(b) Preparation of Hull for Coating

A good coating system starts with a properly prepared steel surface. In the case of new construction, cleaning of the steel is relatively easy. Ship sections are constructed and then blast cleaned in a shop under a controlled environment. Individual plates may also be blast cleaned by a shot or grit blasting machine and primed in the shop to prevent rusting. The plates are then cut to shape and welded together in sections to form the hull.

On existing ships that must be recoated in dry dock, salt, rust, oil, grease, marine fouling, and other contaminants must be removed. This is achieved by a combination of methods which may include the following:

- Solvent wipe to remove oil and grease;
- Water wash with fresh water to remove salts, fouling, and loose rust;
- Wet or dry abrasive blasting to remove rust, fouling, and old paint;
- Hand and power-tool cleaning to remove rust and scale from small areas and too-smooth weld areas.

Solvent cleaning is usually performed manually by first removing heavy oil or grease with a scraper. This is followed by spraying the surface with solvent and scrubbing with rags or brushes. Alkaline or emulsion cleaners are also used to remove oil and grease.

Steam cleaning, utilizing steam or hot water under pressure with a detergent or alkaline cleaner, will remove oil greases, and soaps by thinning them with heat, emulsifying them, and diluting them with water.

High-pressure water cleaning is used to remove fouling, rust, loose paint, and salt. The pressures used normally exceed 138 bar (2,000 psi), with water flow rates of 2 to 3 L/min (9 to 13.6 gpm). Cleaning rates are typically 150 sq m/h (1,600 sq ft/h), depending upon the nature of the hull surface(31). Abrasives may be added to increase the efficiency of the blast cleaning.

To prevent flash rusting, chemical inhibitors may be added to the water to passivate the steel.

Abrasive blast cleaning is achieved by forcing particles entrained in air through a nozzle onto the area to be cleaned. The high-speed particles remove rust, old paint, scale, and marine fouling. Cleaning rates are high, and a very clean surface is produced.

Hand and power-tool cleaning include steel-blade scrapers, wire brushes, air hammers power discs, and power brushes. The production rate for cleaning is low for these tools. Their use is limited to small areas.

The steel is usually cleaned to the Steel Structure Painting Council (SSPC) Specifications which detail the surface preparation requirements, from solvent cleaning to abrasive blast cleaning. Pictorial standards are available to supplement the Specifications. The Swedish Standards are photographs that exhibit the different degrees of blast cleaning. The National Association of Corrosion Engineers (NACE) has plastic-encased, blast-cleaned steel coupons that can be used in conjunction with the SSPC Standards.

Most coatings applied to hulls require a near-white, blast-cleaned finish (SSPC-SP10, Swedish Sa2-1/2 or NACE No. 2). However, in practise, most shipyards may be able to achieve only a good commercial blast finish (SSPC-SP6, Swedish Sa2, or NACE No. 3) because of less-than-ideal conditions in the dry dock.

For most coatings used on ship hulls, blast cleaning achieves a maximum surface profile of 40 microns (where 1 micron is equal to 0.001 mm). This is adequate, since most conventional hull coatings rarely exceed 200 microns (8 mils, where 1 mil is equal to 0.001 in). For heavy-duty icebreaker coatings, profiles of 75 microns are required. This provides better mechanical adhesion between the steel and the coating.

(c) Typical Coatings Used on Ships Hulls, Primarily in Ice-Free Waters

The coatings most frequently used as hull coatings are as follows:

- Primers
  - polyvinyl butyral with zinc chromate (etch primer);
  - polyvinyl-butyral phenolic resin with iron oxide, zinc chromate, or a combination of these or other pigments;
  - epoxy with iron oxide;
  - epoxy with zinc dust;
  - silicate resin with zinc dust;

- Anticorrosive	- bituminous, aluminum-pigmented; - vinyl; - chlorinated rubber; - epoxy; - coal tar/epoxy; - polyurethane; - flakeglass epoxy or polyester;
- Antifouling	- rosin base with cuprous oxide - vinyl with cuprous oxide, organo-tin, and/or organic biocides; - chlorinated rubber with cuprous oxide, zinc oxide, and/or organo-tin.

Most of the conventional coating systems, such as the aluminum-pigmented bitumen with a rosin base/cuprous-oxide antifouling, have life expectancies of 18 to 24 months after initial application. The advantages of these coatings are low cost, easy application and repair, and tolerance of poor conditions of application and surface preparation. Their disadvantages are relatively poor adhesion, fair compatibility with cathodic protection, low dry-film build, and low resistance to erosion. The relative softness of the coatings combined with the aforementioned disadvantages result in a shorter life expectancy than the high-performance coatings.

Vinyls are not as widely used as the other more sophisticated hull coatings. They possess very good resistance to water and chemicals. For underwater use, it is generally recommended that they be applied at least 200 microns (8 mils) thick. The disadvantages of the vinyls are that they are sensitive to poor surface preparation and surface moisture. They must also be applied over a pretreatment primer because their adhesion to bare steel is poor. An advantage of the vinyls is easy maintenance. Recoating existing vinyls is not difficult, since the solvent in the new coat will usually ensure good adhesion with the previous coat.

Chlorinated rubbers are more widely used than the vinyls They share some of the same characteristics with the vinyls - good chemical and water resistance, single pack application, and good adhesion to previous coats of chlorinated rubber. Chlorinated rubbers are more tolerant of poor surface preparation and application conditions than vinyls.

Epoxies are usually more expensive than the other hull coatings, but they exhibit improved resistance to chemicals, water and abrasion, and allow high build. The systems are two-component consisting of a resin and a curing agent. Because of this, the application of the epoxy is usually by special twin-feed spray equipment normally heated to decrease the viscosity.

Coal-tar epoxies have advantages over pure epoxies in improved water resistance and lower cost. The resistance of the coal-tar epoxies to alkaline conditions is better than bitumens because of the epoxy component. This improves their compatibility with cathodic-protection systems. Other advantages include high solids content and good resistance to solvents.

Polyurethanes are similar to the epoxies in being two-component coatings with good chemical, water, and abrasion resistance. They have an advantage over the epoxies in curing at lower temperatures. A disadvantage is that they are more sensitive to surface preparation than the epoxies.

The addition of flakeglass to epoxies merely improves the corosion-inhibiting properties of the coating. The platelets of glass increase the distance moisture must travel through the coating to the steel. Flakeglass polyesters exhibit similar properties to the epoxies. They are tough, abrasion and chemicalresistant coatings which are compatible with cathodic protection.

Antifouling paints are designed to release toxins into the seawater to prevent the growth of weeds and animal organisms on the hull. There are basically two types. The first type consists of a vehicle such as a rosin base, vinyl, or chlorinated rubber that releases a toxin into the seawater. The second type reacts by dissolving both the vehicle and the toxin.

Typical toxins used include cuprous oxide, organotins, and organic biocides. They are usually used in combination, since the toxins behave differently with the various shell and weed fouling.

The coating systems that are suitable for ships travelling in ice-free waters are not suitable for the high impact and abrasion areas of icebreaker hulls. These areas of the icebreaker hull include the bow area, the waterline, and to some extent, the stern

The conventional coatings do not possess the adhesion, abrasion and impact resistance, the high film build, and the toughness required of a coating for service in ice. Coatings that do not possess these properties are removed by the ice very quickly. Several of the coating types do exhibit some of the qualities required, particularly the epoxies and polyurethanes. With improvements, these coatings could be made suitable for service in ice-covered waters.

B. DESIRABLE CHARACTERISTICS OF COATINGS FOR SERVICE IN ICE-COVERED WATERS

An effective coating suitable for service in ice-covered waters must exhibit the following characteristics;

- Excellent abrasion resistance;
- Good resistance to impact;
- Good resistance to underfilm corrosion at damaged areas;
- Excellent adhesion to steel;
- A low coefficient of friction;
- Tolerance of less-than-ideal coating-application conditions;
- High coating build in limited passes;
- Easy cleaning of marine fouling with no coating damage;
- Fast curing time;
- Compatibility with cathodic protection.

The ideal coating must have good resistance to both abrasion and impact from the ice particles. Abrasion can be separated into two processes: cutting and deformation(32). At a low angle of incidence, the particles will cut the coating; at a high angle of incidence, the coating will deform and, eventually, fracture. Cutting is a function of the coating hardness. Deformation is related to the modulus of elasticity. Low-modulus coatings will deform sufficiently to relieve the stress. Therefore, the coating must be harder than the ice particles to resist cutting, yet sufficiently elastic to deform and reduce the stress from impact. The short-term hardness of ice at a loading interval of 10^{-4} s is 5,000 g/sq mm (7,100 psi)(32). For comparison sake, lead has approximately the same hardness. Coatings with a hardness greater than this and a low modulus would be resistant to ice abrasion.

Adhesion of the coating to the steel and underfilm corrosion are interrelated. Underfilm corrosion, or undercutting, is the penetration and spread of corrosion at a defect or unprotected edge of the coating. For this to occur, the force exerted by the corrosion reaction must exceed the adhesive strength of the coating to the steel. Adhesion is also important for the coating to resist the forces exerted by the ice. A coating with high adhesive strength will resist being pulled away from the steel better than one with a low adhesive strength.

The coefficient of friction between the hull and the ice is very important to an icebreaker. A low coefficient of friction reduces the power required to break ice, increases fuel efficiency, and reduces the opportunity of the ship becoming "stuck" in the ice. The U.S. Coast Guard study by S.J. Calabrese reported that the coefficient of friction could be greatly reduced if the hull was coated with suitable coating systems(33).

Three friction coefficients were studied by Calabrese: breakaway, static, and kinetic. The breakaway coefficient of friction is the value associated with a ship as it breaks free of the ice after an extended period of contact. The static coefficient of friction is taken immediately after the ship breaks away from the ice. The kinetic coefficient of friction is measured with the ship in motion.

For steel the coefficients are approximately the following:

- Breakaway: 0.8;
- Static: 0.4;
- Kinetic: 0.1.

These values are dependent upon the surface roughness, ice condition, temperature, and time in contact. Coatings such as polyurethanes, polyethylene, polyphenylene oxide, and others reduced the coefficients to the following:

- Breakaway: <0.4;
- Static: <0.15;
- Kinetic: <0.08.

On existing ships, coatings must be applied in the dry dock, where conditions are less than ideal. Conditions must be warm and dry for the coatings to adhere to the steel and to cure. The ideal conditions would be temperatures approaching 20°C, with a relative humidity less than 85%. With these conditions, most coatings would cure quickly and properly. However, shipyards often are working under a tight schedule to put the ships into the water within several days time. They often do not have a choice, except to apply the coating when the weather is cold and damp. Therefore, the coating must be tolerant of low temperatures, high relative humidity, and less-than-perfect surface preparation. Unfortunately, most coatings are sensitive to poor conditions. Shelters are often constructed to shield the hull from poor weather and are heated to provide conditions that are suitable for coating application. Often, ships are coated under a covered dry dock.

Most coatings are high in solvent concentration. Typically, coatings contain 30% to 70% solvent by volume. The high solvent content prevents most coatings from being applied thicker than 125 microns (5 mils). At excessive wet-film thicknesses, such coatings will run and sag. Solvent entrapment, wrinkling, cracking, and disbonding are other problems associated with excessive film build. Epoxies and polyurethanes are particularly susceptible to cracking and disbonding due to the internal stresses that are caused by internal shrinking during the curing process, if excessive film thicknesses are achieved.

The icebreaker hull coatings must overcome these problems to be applied in a minimum number of coats to a thickness of at least 500 microns (20 mils). Minimizing the number of coats reduces the chances of intercoat delamination. Delamination is caused by contamination of the undercoat, incompatibility between coats, and over curing the undercoat which prevents chemical bonding to the topcoat.

High coating build is desirable to ensure that all areas of the hull are isolated from the seawater; particularly, on very rough, corroded hull surfaces. A thick coating will cover the peaks better than a thin coating. On severely corroded surfaces, a filler material is often needed to assist the coating system because even a 500 to 750-micron (20 to 30-mil) coating may not adequately cover all areas.

The coating must possess fast "dry-to-touch" and curing rates. The coating should skin over within several hours to prevent moisture, either as condensation or rain, from adversely effecting the performance of the coating. The time for a full cure should be as short as possible, since time in dry dock is not productive time to a ship owner. Coatings that are designed for use in ice must be completely cured before entering the water, otherwise premature coating failure will occur.

Marine fouling in the form of weeds or animal organisms increases the roughness of the hull and reduces the operating efficiency of the ship. Fouling may also destroy a conventional coating by penetrating the coating to adhere to the underlying steel.

For ships travelling in ice, fouling is not a serious problem since the scouring action of the ice will remove the weeds or barnacles from most areas of the hull. However, when the ship is not breaking ice, it will quickly foul when moored at a dock or proceeding in open water. An icebreaker may break ice for as little as 1000 hr per operating season, and the rest of the year will be spent either at dock or travelling in ice-free waters to areas where its service is needed. Typically for some Arctic icebreakers, a season may consist of 5000 hr of service breaking ice.

Most antifouling systems are not worthwhile for ships travelling in ice-covered waters. The ice will quickly remove the antifoulant in those areas of the hull that are abraded by the ice. Usually, it is more practical to use underwater cleaning techniques to remove the fouling. The coating should, therefore, be hard enough to resist penetration by fouling organisms and tough enough to resist damage during cleaning.

Compatibility with cathodic protection is desirable for any hull coating system because, in most cases, the coating can not provide complete protection to the steel. Coatings are damaged and where breaks occur in the coating, corrosion can proceed on the steel. This is particularly important in the highly oxygenated cold waters of the Arctic, where corrosion rates are high and can be increased further by the potential differences that exist between welds and the parent metal.

Cathodic protection is usually applied to the hulls to compensate for the deficiencies in the coating systems. The coating must, therefore, possess good resistance to alkaline conditions, since the reaction at the cathode produces the hydroxyl ion (OH^-) which increases the pH of the water near the cathode (steel). Chlorinated rubbers will blister if exposed to potentials approaching -1.1 volts referred to a silver/silver-chloride reference electrode because of the alkaline conditions and electroosmotic action.

The coating must also be able to resist blistering caused by hydrogen evolution at the steel. At potentials approaching -1.2 volts, gaseous hydrogen is generated at the cathode. The hydrogen gas can cause the coating to blister. The adhesive strength of the coating to the steel must be greater than the forces exerted by the gas.

Epoxies, particularly the 100%-solids group, are virtually unaffected by potential shifts of 0.4 volts and have been found to be unaffected by potentials of -2.0 volts to silver/silver-chloride(34).

C. DEVELOPMENT OF COATINGS FOR SERVICE IN ICE-COVERED WATERS

The development of coatings for service in ice-covered waters began in the early 1970s in the United States and Europe.

The United States Coast Guard (USCG) initiated a three-part study in 1972 at Rensselaer Polytechnic Institute in Troy, New York(33). The study was conducted by S.J. Calabrese over a period of six years. Its main purpose was to identify and evaluate low-friction coating materials that would be sufficiently abrasion resistant for icebreaker hulls. The study was conducted in three phases, each lasting approximately two years.

1. USCG Study - Phase I (1972 - 1974)

Phase I was concerned primarily with the identification, development and evaluation of low-friction coating materials. Part I of the first phase involved laboratory studies on frictional behavior, hardness, and abrasion resistance. Part II involved full-scale field tests using the successful coatings from Part I on the hulls of two USCG icebreakers.

(a) Laboratory Tests

The first series of tests used a modified-ore crusher to simulate the impact abrasion of ice on the coatings. Figure III-1 shows the test rig used to simulate the crushing and sliding action of ice on the coatings. The rig consisted of two plates that are mounted at an angle to each other. One plate is mounted on an eccentric so that compound motion results with movement both parallel and normal to the fixed plate. Coated test plates were mounted on the oscillating face of the test apparatus, and 45.5 kg (100 lbs) of ice were run through the machine for each sample.

It was recognized that even though the motions of the test rig were similar to actual conditions on an icebreaker's hull, the velocity and, therefore, the dynamic stress on the hull would be much higher. This did not detract from the usefulness of the test, since it was designed to screen those coatings not suitable for

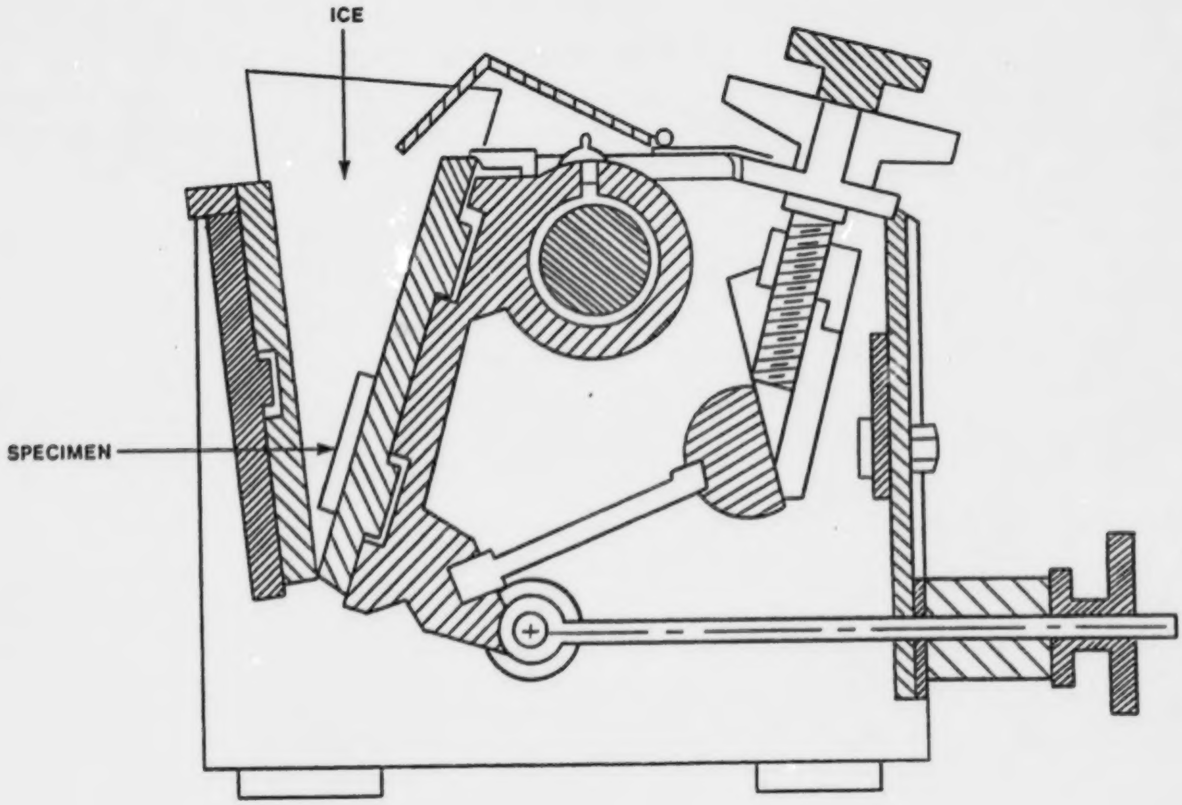

ICE
SPECIMEN

FIGURE III-1 - ICE-CRUSHING TEST RIG

TABLE III-1

MATERIALS TESTED FOR ABRASION RESISTANCE TO ICE (USCG STUDY)

MATERIAL	TRADE NAME	MANUFACTURER
Phenolic Paper and Canvas Laminate	Textolite	---
Graphite-Filled Phenolic	Insurok	---
Polyester	Valox	---
Modified Polyphenylene Oxide	Noryl	General Electric Co.
Teflon-Filled Acetal	Delrin A/F	DuPont Co.
Acrylic	Plexiglass	---
Nylon and Nylon With Molybdenum Disulphide	---	---
Nylasint - Porous Nylon	Nylasint	Polymer Corp.
Polycarbonate	Lexan	General Electric Co.
Polyvinyl Fluoride	Kaynar	Fluorocarbon Co.
Polyolefin	Pennlon	Dixon Corp.
Polyethylene - HMW	Polypenco	Polymer Corp.
Teflon and Filled Teflons	Chemplast Dixon Rulon	--- --- ---
Urethane	1A to 8B	Goodyear
Polyethylene Copolymer	8078-1, 2, 3 & 4	Dow Chemical
Silicones	3404, SS-4191, 8471 & SCS-1600	General Electric Co.

- continued -

TABLE III-1 (continued)

MATERIALS TESTED FOR ABRASION RESISTANCE TO ICE (USCG STUDY)

MATERIAL	TRADE NAME	MANUFACTURER
Epoxy	201 primer 204 primer 224 topcoat	Devoe and Reynolds
Epoxy With Fillers	ESL-1 to 9 345-51	Esso
Ice-Release Coatings (Teflon Filled)	#1 to #4 (15% to 38% TFE)	U.S. Naval Research Lab
Polyurethanes	Dexter	Dexter Corp.
	Cermet filled	Dexter Corp.
	Teflon filled	Dexter Corp.
	Crandalon	Crandalon
	Chemglaze	Hughson Company
Glass-Flake Polyester	---	Baltimore Copper Paint
Cold Plastic	YSP-19-7	U.S. Coast Guard
Vinyl	---	U.S. Coast Guard
Primer, Epoxy, and Polyurethane System	---	Devron
	Dimetcote #3, #6	Dimetcote
	Ameron #4	Ameron
	Ameron #5	Ameron
	Carbozinc #11	Carboline
Coal-Tar Epoxy	300-M	Koppers
Coal-Tar Epoxy	C-200 305-AF	Porter
Solid Film Lubricant With Molybdenum Disulphide	200-1 200-23	Microseal

- continued -

TABLE III-1 (continued)

MATERIALS TESTED FOR ABRASION RESISTANCE TO ICE (USCG STUDY)

MATERIAL	TRADE NAME	MANUFACTURER
Vinyl With Molybdenum Disulphide	42-271	Stan Chemical
Plasma Spray	Aluminum	---
	431 SS	---
	Tungsten carbide with lubricant	Artech
Teflon/Halon	---	Zitex
Teflon Tape	---	---
Teflon Powder and Aerosol Sprays	---	---
Silicone Wax	---	---
Carnanba Wax Plus Silicone Wax	---	---
Coal-Tar Epoxy and Polyethylene Powder	---	---

under ice conditions. It was reasoned that coatings which did not pass this test would not withstand the rigors of breaking ice.

The coatings and materials tested are listed in Table III-1. To evaluate each material, surface roughness measurements were taken before and after the test.

The materials that showed the most promise were the following;

- Noryl polyphenylene oxide (0.25 mm thick);
- Goodyear #7A urethane plus slip agent (0.50 mm);
- Dow copolymer plus 25% high-slip polymer (0.05 mm);
- Microseal bonded molybdenum disulfide (0.025 mm);
- Naval Research Lab fluorinated resin 26% TFE (0.125 mm);
- Dexter high-gloss polyurethane (0.2 mm);
- Dexter polyurethane plus Cermet (0.2 mm);
- Dexter polyurethane plus Teflon (0.2 mm);
- Crandalon polyurethane (0.2 mm);
- Hughson polyurethane (0.15 mm);
- Koppers bituminous epoxy (1.0 mm).

The polyurethanes, modified polyphenylene oxide, and the bituminous epoxy showed no detectable damage with very little change in surface roughness. The others exhibited fine scratches, slight scuffing, or slight chipping. In the case of the Goodyear urethane, it deformed due to the elastic nature of the urethane, but recovered its smoothness after 24 hours.

The second series of tests in Part I involved the study of the frictional behavior of materials sliding against ice. These materials included steel, the successful coatings from the abrasion test, and other products.

Rings of the test material (51 mm OD by 32 mm ID) were mounted in a test rig which was attached to and driven by a drill press. The rig was mounted in a cold box on a flat plate of ice. The cold box was chilled by a refrigeration unit circulating Freon in coils around the box. The housing holding the sample ring was free to rotate against the ice.

The temperature of the ice was controlled by means of a thermocouple on the ring housing, a variac, and a tape heater wrapped around the housing to quickly change the temperature.

A load cell was used to measure the load on the rings. Torque was measured by strain-gauged torque beams and recorded on a chart recorder.

Different forms of ice were used in the tests: solid ice, ice particles, ice chunks, and snow. The rationale behind using different types of ice was a suggestion that a ship's hull is actually separated from solid ice by a layer of crushed ice.

Three values of friction were measured on each sample: breakaway, static, and kinetic. The first samples tested were steel. The following conditions were varied to determine the effect on the friction coefficients:

- Ice condition;
- Load;
- Surface roughness;
- Temperature;
- Time in contact.

Steel with a roughness of 3.3 microns (0.13 mils) under a load of 41 kg (90 lbs) on solid ice at -25°C (-13°F) has the following coefficients of friction:

- Breakaway: 0.8 ± 0.07;
- Static: 0.4 ± 0.05;
- Kinetic: 0.1 ± 0.02.

Load has virtually no effect on the kinetic coefficient of friction between 13.6 kg and 90.9 kg (30 lbs and 200 lbs). The static friction coefficient was also unaffected, except on rough steel (6.1 microns [0.24 mils]) where it increased until it levelled off at loads of 22.7 kg (50 lbs) or greater. The behavior of the breakaway friction coefficient was similar on the rough surface. At loads greater than 40.9 kg (90 lbs), the coefficient levelled off at 1.2.

Surface roughness of the steel has a significant effect on the breakaway and static coefficients of friction. The coefficients are three times higher with a roughness of 6.1 microns (0.24 mil) than with a roughness of 1.0 micron (0.04 mil). This effect can have practical significance for a ship travelling through ice. A ship's hull is usually very rough because of corrosion and fouling. Every time a ship begins to move through an ice field, very high values of breakaway and static friction coefficients would be experienced. If the corrosion pits are not filled in and the hull is coated, the coating could still be subject to frictional coefficients of 0.8 to 1.2. This would, in all likelihood, reduce the life of the coating system (ice could develop a better grip to the hull, thereby, increasing the force exerted on the coating). Surface roughness could be reduced by first filling in the pits with a filler compound and then applying the coating.

Surface roughness had very little effect on the kinetic coefficient of friction.

A temperature variation of -2°C to -25°C (28°F to -13°F) had virtually no effect on the kinetic friction coefficient. The breakaway and static coefficients decreased slightly as the temperature was increased from -25°C to -7°C (-13°F to 19°F). However, at -7°C (19°F), both coefficients exhibited a significant reduction because of a reduction in the specific adhesion and shear strength of the ice. On a smooth steel surface (1.0 micron), the values decreased to 0.1. On a rougher surface of 3.3 microns (0.13 mils), the coefficients decreased within the temperature range of -7°C to -2°C (19°F to 28°F). At -2°C (28°F), the coefficients increased significantly because of the large asperities on the steel surface embedding into the low-strength ice.

To apply this condition to an icebreaker hull suggests that maintaining the hull roughness at no more than 1 micron would assist in reducing hull friction.

The type of ice did not significantly affect the coefficients of friction. There was no influence on the kinetic value. The static value increased as the contact area increased (higher for the snow and ice particles than for solid ice).

Once the tests were completed on the steel samples to determine the influence of the various factors on the frition coefficients, a large number of materials were evaluated to establish their coefficients of friction. Four frictional coefficients were taken for each sample, including the following:

- Long-term breakaway (after 30 min in contact);
- Short-term breakaway (after 1 minute in contact);
- Static friction;
- Kinetic friction.

The only factor that was varied during the tests was the load. The coefficients were measured at loads of 13.6, 22.7, 40.9, 68.2, and 90.9 kg (30, 50, 90, 150 and 200 lbs). The temperature was maintained at -22°C (-8°F). The surface roughness was dependent upon the nature of the coating. It varied from a very smooth surface of 0.05 micron (0.002 mil) to a rough surface of 12.7 microns (0.5 mil).

At the end of the tests, each sample was given a detailed microscopic examination to determine the surface damage. The damage was categorized as follows:

- Severe Deformation: This damage was found on the softer solid materials and involved deformation and smearing. This was found on the Teflon and polyethylene;

- Spalling: This involved the coating separating from the steel substrate and was found on the Teflon and epoxies;

- Pitting:	The materials which showed this type of damage were the phenolics, acetals, polyesters, and epoxies. Small areas of the coating were removed;
- Heavy Scoring:	The surface was severely scored, producing plow-out scratches and large amounts of surface debris. This was seen on the phenolics, acrylics, nylon, and polycarbonates.
- Light Scratches:	The surface showed very light score marks which were narrow and shallow. The polyurethanes, polyphenylene oxide, and polyvinyl fluoride exhibited this type of damage.

It was concluded from the tests that the coatings exhibiting low frictional coefficients with the least amount of surface damage would perform the best as icebreaker hull coatings.

The coatings that were judged as being potential icebreaker hull coatings were the following:

- Polyphenylene oxide;
- Polyurethanes (Crandalon, Goodyear 7b, Hughson);
- Polyurethane/TFE (Dexter);
- Polyurethane/Cermet (Dexter);

- Bituminous (Koppers 300-M);
- NRL Teflon #2.

The polyethylene was also selected as a potential hull coating because of its low friction coefficient. It was damaged during the tests; however, it was hoped that it could be bonded with an abrasion-resistant material.

The aforementioned coatings reduced the friction coefficients to the following values:

- Breakaway: 0.02 - 0.4
- Static: 0.02 - 0.15
- Kinetic: 0.02 - 0.08

The most significant reduction is seen in the breakaway and static values. The reduction is at least one half. This is significant since an icebreaker will require less power to break through the ice, and the chance of becoming lodged in the ice is much lower if a hull coating is used.

The candidate coatings were then subjected to the same frictional tests at a load of 90.9 kg (200 lbs) at temperatures varying between -22°C and -2°C (-8°F and 28°F). The results were similar to the tests done on the steel. The rougher or softer coatings (polyethylene, solid Teflon, and Goodyear #7b polyurethane) showed an increase in friction above -10°C (14°F). The harder, smoother polyurethanes, solid acrylic, polyphenylene oxide, and bituminous coatings remained unchanged or exhibited a decrease in friction above -10°C (14°F).

As a final test for the potential coatings, they underwent long-term ice abrasion testing. The coatings tested were the five that showed the most promise after the frictional tests involving temperature variation (three polyurethanes, Koppers 300-M bituminous coating, and the polyphenylene oxide) and three epoxies (#201, 204, and 224 from Devoe). Coated samples were placed in rock tumblers charged with ice chunks and run continuously at -18°C (0°F) until 120 hours were reached or the coating failed.

The purpose of the test was to establish relative wear rates for the coatings. To this end, the samples were removed and weighed every 24 hours.

The epoxies and the polyurethane/Teflon spalled within the first 24 hours. The polyurethane/Cermet and the Koppers bituminous 300-M exhibited signs of edge chipping, but were otherwise intact after 120 hours. The lowest wear was shown by the polyurethane (unfilled) and the modified polyphenylene oxide.

Scratch-hardness tests using a Teledyne Taber Shear-Scratch tester were conducted to correlate the wear or damage properties of the coatings to hardness. However, no conclusive correlations could be established other than the best coatings were those that had a scratch hardness greater than lead.

To summarize Part I of the first phase of the United States Coast Guard study, the following results were obtained:

- The most promising of the coatings were the unfilled polyurethanes and the modified polyphenylene oxide. They gave low frictional coefficients of less than 0.15 for static and kinetic values. Steel under the same conditions produced values between 0.10 and 0.40. The two coatings also resisted damage, wear, and spalling during the abrasion tests;

- An optimum hardness value appears to exist for materials used to resist ice abrasion. Coatings softer than ice are easily damaged and give high friction values near 0°C (32°F). Hard coatings, such as some epoxies, are chipped and pitted by ice. The value seems to exist somewhere between the two;

- The frictional behavior of coated surfaces in contact with ice appears to be affected by three primary factors: temperature, time in contact, and surface roughness. To a lesser extent, load and ice conditions have an effect on the coefficients of friction;

- Significant reductions in friction can be obtained by using a smooth, corrosion-resistant surface when travelling through ice.

(b) Full-Scale Tests

Part II of Phase I was concerned with full-scale tests on two United States Coast Guard icebreakers. In November 1973, three coatings were selected from Part I to undergo field tests:

- Dexter Polyurethane X500-4R1 over a polyurethane primer and a zinc-rich polyamide epoxy primer;

- Goodyear Polyurethane D1666F302 over a Devron 201 epoxy primer;

- General Electric polyphenylene oxide over a zinc-rich polyamide epoxy (Hughson Chemical 9922).

Two polyurethanes were selected because they represent the opposite ends of the polyurethane system. The Goodyear coating is an elastomer that was developed as a low-friction coating. The Dexter polyurethane is a hard, tough coating.

i. USCG Cutter Yankton

The Goodyear polyurethane was applied to the USCG Cutter Yankton during cold, wet weather in the first week of November. The coating system was applied to a white metal, grit blast-cleaned surface. Once an area of the hull was cleaned, the epoxy primer was applied to a dry-film thickness between 64 and 102 microns (2.5 and 4.0 mils). This was followed by six coats of polyurethane topcoat, each 76 to 102 microns thick (3.0 to 4.0 mils).

The temperature varied between 3°C and 17°C (38°F and 52°F) during the day. At night, the temperature was near the freezing point. Relative humidity varied between 59% and 100%.

The bond strength of the coating was approximately 41 bar (600 psi). This was the minimum adhesive strength of the coating system because failure always occurred in the epoxy not in the polyurethane or at the interface between the epoxy primer and the polyurethane. The tensile strength of the polyurethane was reported to be 166 bar (2,400 psi).

The roughness of the hull was measured to be 10 microns (0.4 mil) or greater after grit blasting. Coating the hull reduced the roughness to less than 2 microns (0.09 mil). This measurement did not include welds or severely pitted areas. Pitting was measured to be as deep as 2.54 mm (0.1 in) in areas. The pits in these areas were not filled because of the cost and time involved.

After 35 hours of icebreaking service near Bangor, Maine, the Yankton was dry docked. The hull was examined and it was found that the Goodyear polyurethane was completely removed at the bow near the ice line and approximately 80% around the ship. The only area where it remained at the ice line was at the stern. The cause appeared to be a lack of bond to the epoxy undercoat. There was no chemical adhesion between the two coatings.

Samples of steel were cleaned and coated at the same time the ship was coated in dry dock. Examination of these samples indicated good adhesion between the epoxy primer and the polyurethane. The only differences between the coating on the hull and the coating on the samples were that the hull was immersed after application, and the hull coating was subjected to subzero temperatures during the cure, while the samples were eventually brought indoors after they had supposedly cured. This suggests that the cold, damp conditions in the dry dock prevented a chemical bond from developing between the primer and topcoat. It may also have prevented the coatings from reaching a full cure. This emphasizes the importance of the environmental conditions during application of coatings to ships travelling in ice-covered waters.

ii. USCG Cutter Sauk

The second ship coated during the field tests was the USCG Cutter Sauk. It was to have been coated with the Dexter polyurethane and the modified polyphenylene oxide. However, difficulties occurred after priming the hull with the zinc-rich polyamide epoxy. The epoxy was dampened by a fog, and the polyphenylene oxide would not adhere to the surface. As a result, the entire hull was coated with the Dexter polyurethane due to time restrictions.

The environmental conditions were cold, but clear, during application of the epoxy primer and the polyurethane. Temperatures were -1.0°C to 10°C (30°F to 50°F) during the day. At night, temperatures dropped to -1.0°C (30°F). Relative humidity was not a problem. It varied between 50% and 65% during the day.

The epoxy primer was applied very thin to ensure a chemical and mechanical bond between it and the steel substrate. The thickness was less than 25 microns (1 mil). After the primer was cured for three hours, the first coat of polyurethane was applied. In total, three coats of polyurethane were applied at a total thickness of 165 to 216 microns (6.5 to 8.5 mils). The ship was then allowed to sit in dry dock for four days before putting it back into the water.

The surface roughness on the hull (nonpitted areas or welds) was reduced from greater than 10 microns to 1.5 microns (0.4 mil to 0.06 mil) after the three coats of polyurethane. The coating was used to fill in shallow pits, but it was insufficient to fill in the pits deeper than 2.54 mm (0.1 in).

The bond strength of the coating system was at least 29 bar (425 psi). The epoxy primer exhibited cohesive failure on a sample of steel coated in the dry dock. Other samples coated with the polyurethane failed in the adhesive epoxy at between 32 bar and 39 bar (470 psi and 565 psi). This indicated that the weak link in the system was the epoxy adhesive, therefore, the bond strengths are minimum values.

After 40.25 h of icebreaking, the ship was inspected while in the water. It had broken both hard ice and pack ice. The coating was in fair condition in the bow area, with a 102-mm (4-in) wide band of polyurethane still intact. Below it, a band of polyurethane at least 152 mm wide (6 in) was removed to a distance of 3 m (10 ft) from the bow. Approximately 6 m (20 ft) from the bow, about 90% of the coating was still intact at the water line. From midship to stern, the coating was 100% intact at the water line.

(c) Conclusions

The conclusions drawn from the full-scale tests were the following:

- A polyurethane with little cross-linking (nonelastic material) produces a better bond to a primer and shows less wear during icebreaking than an elastic polyurethane;

- Application conditions are important to the performance of the coating;

- Surface roughness of the hull can be reduced to 1.5 microns (0.06 mil) using a polyurethane coating. As a result, friction is reduced;

- Two areas of wear were seen on the hull. The first area is at the bow where the coating is subjected to impact loading above and below the water line. The Dexter polyurethane withstood this type of wear in that no severe damage was noted. The second area of wear is at the water line. Pack ice abraded the area between the bow and midship. Additional protection is needed in this area;

- A coating with a friction coefficient of 0.3 or less and a bond strength of at least 29 bar (425 psi) will withstand abrasion during "hardice" breaking. A coating with these same properties will not withstand "pack-ice" service.

2. USCG Study - Phase II (1974 - 1976)

The second phase of the study was divided into three parts. Part I involved the continuation of the effects various factors have on the frictional coefficients including velocity, humidity, coating thickness, and surface area. Part II pertained to the continuation of full-scale tests on potential icebreaker coatings. Part III studied mush or particulate ice. A summation of Part III has not been included in this report.

(a) Laboratory Tests

In Part I, the first factor studied in the laboratory was velocity and its effect on friction. The velocity of a ship travelling through ice is usually dictated by safety. Depending upon the condition of the ice, the speed is usually 5.2 kn to 10.4 kn (6 mph to 12 mph). At slower speeds, the ship may become stuck in the ice. The ship would then have to proceed under high power to ram itself free of the ice.

Using the test rig from Phase I, rings of bare steel were prepared at different surface roughnesses and tested at different velocities. As the velocity approached 1.7 kn (2 mph), the frictional coefficient was reduced from the static value of 0.3 to 0.4 to approximately 0.1. At a given speed, the smoother steel produced a lower coefficient of friction than the rougher steel.

Similar tests were run on coated and solid rings of various materials including polycarbonate, nylon, Teflon, glass, acrylic, polyurethane, and a copolymer. The coatings were tested on both rough and smooth (0.25 micron or 0.01 mil) ice.

The coatings and materials exhibited behaviour similar to the steel samples. As the velocity increased, the coefficient decreased to 0.1 or less. The velocity at which each material attained this value varied from less than 0.4 kn to 1.3 kn (0.5 mph to 1.5 mph). The roughness of the ice and the type of material influenced the value of the coefficient as the velocity increased. Teflon reached a coefficient of 0.1 or less at velocities less than 0.4 kn (0.5 mph), regardless of ice condition; whereas, polycarbonate required a velocity of 0.4 kn to 0.9 kn (0.5 mph to 1.0 mph) before the coefficient was reduced to 0.1 or less. An increase in ice surface roughness reduced the coefficient to 0.1. It was suggested that very smooth surfaces stick together at extremely low velocities, thereby, increasing the friction coefficient.

On all previous tests, the relative humidity was controlled at less than 10%. However, under actual icebreaking conditions, the humidity is a variable. Using the same test apparatus with the addition of a drying tower, a water reservoir, and an air source, the relative humidity was varied from 10% to 50%.

The test results indicated that low humidity and low velocities combined to produce the highest coefficients of friction for steel and coated samples. At velocities less than 0.4 kn (0.5 mph), the coefficient of friction was highest for a relative humidity of 10%. Increasing the humidity to 30% or 50% reduced the coefficient.

The results suggested that moisture condensing on the ice surface formed a film between the sample and the ice. This process had a greater effect on reducing the coefficient of friction at lower velocities. At higher velocities, the frictional heat provides water at the surface, and therefore, condensed moisture's effect is reduced.

The area of contact between the steel or coating and the ice influences the coefficient of friction. At low pressures, the contact area between the steel and the ice is not complete, and the steel contacts the ice at the peaks on the ice surface only. The friction coefficient remains constant, since the contact area increases proportionately wih the load, and the coefficient can be expressed as:

$$f = \frac{A_r S}{L}$$

where f = frictional coefficient;

A_r = real area of contact;

S = shear strength of the ice;

L = load.

Eventually, a point is reached where the pressure reaches the yield strength of the ice, and the actual area of contact approaches the full area as defined by the specimen geometry. At this point, A_r becomes constant, and since S is a constant as well, the friction coefficient decreases as the load or pressure increases. Therefore, the coefficient of friction is constant at low pressures, but at the high pressures experienced when breaking ice, the friction coefficient is reduced. This applies to both static and kinetic coefficients.

The last variable that was tested was the coating thickness. An epoxy polyamide was applied to steel samples at thicknesses of 51, 508, and 1,524 microns (2, 20, and 60 mils). At a temperature of -17°C (1.4°F), relative humidity of 5%, a load of 31.8 kg (70 lbs), and a surface roughness of 0.5 microns (0.02 mils), the friction coefficient was not significantly affected by the variation in coating thickness. The velocity was varied from 0 kn to 2.6 kn (3 mph). The static coefficient was approximately 0.3, and as the velocity increased, the kinetic coefficient decreased to about 0.1 at 0.9 kn (1.0 mph) and remained relatively constant thereafter.

The laboratory tests in Part I continued as new materials and coatings were submitted for testing to determine their suitability for icebreaker service. Several coatings underwent the abrasion test that was used in Phase I of the study to screen acceptable coatings. Included in these coatings were several graphite-filled coatings (epoxy and alkyd), five polyurethanes, a hydrophilic material, a glass-filled polyester, two epoxies, and a Teflon-filled epoxy.

The coatings that showed the most promise following these tests were the Urafilm polyurethane, the Zebron polyurethane, the W2 epoxy, and the Inerta 160 epoxy.

The Urafilm polyurethane, manufactured by Advanced Coating and Chemicals, was applied 711 microns (28 mils) thick. It was a nonsolvented polyurethane similar to those tested in Phase I. The only difference was that the surface roughness of the sample was reduced by grinding from 10.2 microns to 1.8 microns (0.4 mils to 0.07 mils). After the ice-abrasion test, only very light scratches were noted on the surface, and the surface roughness increased slightly to 2.0 microns.

The Zebron polyurethane was the same nonsolvented material that was manufactured by Xenex Corporation under the name, Crandalon, and was tested in Phase I. The only difference was that the material did not have a silica filler added to it. It was applied 889 microns (35 mils) thick. The surface roughness increased slightly, and very light scratches were noted after the abrasion test.

The W2 epoxy was manufactured by Woolsey Marine Corporation. It was applied at a thickness of 254 microns (10 mils) and stood up very well to the abrasion tests. Very light scratches and a very slight increase in surface roughness were noted.

The Inerta 160 epoxy is a two-component, nonsolvented material manufactured by Teknos Maalit Oy in Finland. At a thickness of 406 microns (16 mils), the surface roughness decreased slightly, with no observed damage.

The frictional characteristics of these coatings were then tested. The lowest coefficients of friction were recorded by the Zebron polyurethane. At different loads, the static and breakaway coefficients were 0.10 to 0.12, while the kinetic coefficient was only 0.03 to 0.04.

The Urafilm polyurethane and the W2 epoxy exhibited slightly higher coefficients. The breakaway frictional coefficient varied from 0.2 to 0.25; the static was 0.09 to 0.16; the kinetic was 0.05 to 0.1. The Inerta 160 epoxy was not available for testing.

The last area of study in Part I of Phase II was devoted to coating application conditions, particularly, temperature, surface cleaning, and surface conditions. In most cases, coating application is performed in the dry dock where most variables can be controlled, except for weather conditions. Low temperatures, high humidity, dirt, and moisture on the blast-cleaned steel or uncured coating can affect the performance of a coating system.

To test these factors, six coating systems were selected, applied outdoors, and allowed to cure under three different conditions: outdoors, indoors at 21°C (70°F) and 30% humidity, and at 37.8°C (100°F) in an oven. The six systems were as follows:

- Polyamide epoxy, primer, intermediate coat, and top coat;

- Polyamide epoxy primer, anticorrosion intermediate coat, and vinyl antifouling;

- zinc-rich epoxy primer, anticorrosion top coat;

- Inorganic zinc base coat and coal-tar epoxy top coat;

- Zinc-chromate polyamide epoxy primer and polyurethane (moisture cure) rigid top coat;

- Zinc-chromate polyamide epoxy primer, polyurethane elastomer (chemical cure) intermediate coat, and polyurethane (moisture cure) rigid top coat.

The coatings were applied during warm weather at temperatures ranging from 23°C to 31°C (73°F to 88°F). The relative humidity varied from 65% to 85%.

After curing was complete, adhesion tests were performed on each sample. The epoxy systems and the elastomer polyurethane showed little difference between a cure outdoors or indoors. The bond strengths were 34 bar to 41 bar (500 psi to 600 psi) for these coating systems. The rigid polyurethane, on the other hand, exhibited the largest decrease in bond strength with an outdoor cure. Indoors, a strength of 57.1 bar (830 psi) was developed. Outdoors, the adhesive strength was reduced to 43 bar (623 psi).

Ovencuring the coatings improved the bond strength the most with the rigid polyurethane, the polyamide epoxy, and the coal-tar epoxy. The highest bond strength was noted with the coal-tar epoxy at 118 bar (1,712 psi).

A second series of tests were run on an epoxy and a polyurethane coating system to determine the effect of the following:

- Moisture on a partially cured coating;

- Solvent cleaning between coats after exposure to rain.

Two coating systems were tested:

- Polyamide epoxy primer with chromates, polyamide epoxy intermediate and top coats;

- Modified polyvinyl butyral resin and phosphoric acid wash primer, polyurethane elastomer (chemical cure) intermediate coat, and polyurethane (moisture cure) rigid top coat.

Samples of each coating system were coated and allowed to cure in poor weather conditions (rain) overnight and then cleaned with a solvent (toluene) and top coated. Other specimens were coated without cleaning.

Adhesion tests were then run on the samples. No conclusions were obtained regarding the effect of moisture. Conclusions, however, were obtained for the effect of solvent cleaning. Toluene had very little effect on the bond strength for the polyurethane system. However, the bond strength of the epoxy was reduced by 10 bar to 20 bar (150 psi to 290 psi) from values ranging between 35 bar and 41 bar (510 psi to 595 psi). This was significant, since toluene is a cleaner commonly used to clean equipment used with epoxy paints.

The last series of laboratory tests involved improving the surface condition of the hull by reducing the roughness. Icebreaker hulls are normally very rough because of corrosion in the plate and at welds. The average profiles can exceed 1.27 mm (0.05 in).

To reduce the roughness, the options are as follows:

- Grind the hull smooth;

- Apply a coating material, and grind off the asperities;

- Apply a putty into the pits, and grind them smooth;

- Apply a high-viscosity coating, and squeegee it into the pits.

On very rough hulls, the grinding should be minimized since it is time consuming and costly to grind large areas. The most cost-effective method is to spray on the coating material and squeegee it into the pits.

The coating commonly used as a primer for ship hulls is a zinc-rich polyamide epoxy. In order to increase the viscosity of the epoxy, various filler materials were tried, including the following:

- Aluminum oxide;
- Aluminum and magnesium silicate;
- Aluminum metal powder;
- Silica in several grades;
- Collodial silica.

By adding a filler, it was thought that the epoxy would be more suitable for filling the deep corrosion pits.

The only material that gave satisfactory results with spraying was the collodial silica. The other materials were either not ground fine enough to stay in suspension, produced a surface too rough and nonuniform, or increased the viscosity too quickly so that it could not be sprayed after several minutes. At 3.5 bar (50 psi) nozzle pressure, the epoxy with 1.5% collodial silica, by weight, could be applied by spraying to a thickness of 889 microns (35 mils). To fill in simulated corrosion pits in steel plate, three appliations and squeegee procedures were required.

One disadvantage was noted with the addition of the collodial silica to the epoxy. The curing time was increased by threefold from 16 h to 48 h. This could prove to be a factor in actual applications where dry-dock time constraints are important.

The conclusions reached after Part I of Phase II of the study were the following:

- The coefficient of friction for materials sliding against ice decreases as the velocity increases at low speeds. The coefficient becomes constant, once higher velocities are reached. The rate of decrease in the coefficient is dependent upon the material and the surface roughness;

- Ice roughness does not have a significant effect on the frictional coefficient, except at very low speeds;

- Relative humidity has a significant effect in reducing the coefficient of friction at low speeds. A film of moisture condensing on the ice was attributed as being the cause. At higher velocities where water is already present because of the frictional heat, the effect of humidity is much less;

- The coefficient of friction is constant at low pressures, but decreases once the yield strength of the ice is reached;

- The thickness of a hard coating, such as an epoxy, has no effect on the frictional coefficient;

- Several new coatings were discovered as potential icebreaker coatings including Zebron polyurethane, Urafilm polyurethane, Inerta 160 epoxy, and Woolsey Marine W2 epoxy;

- Application conditions adversely affected the bond strength of the polyurethane when cured outdoors at 23°C and 31°C (73°F to 88°F) and 65% to 85% relative humidity. No effect was noted on the epoxy;

- Toluene was used as a cleaner between coats on an epoxy coating system. The bond system was reduced. No effect was noted on the polyurethane;

- Collodial silica added to epoxy will reduce the roughness of a ship's hull. The viscosity of the epoxy is increased by the addition of the silica, thereby, increasing the thickness that can be applied before it will run. Spraying and squeegeeing the epoxy will fill in pits.

(b) Full-Scale Tests

In Part II of Phase II, full-scale tests were continued on the USCG icebreaker fleet. It was decided that the various polyurethanes from Part I, the Zebron polyurethane from Part II, and two other coatings including a bituminous epoxy and a glass-flake polyester would be tested. The results are as follows.

i. USCG Cutter Yankton

The Goodyear polyurethane elastomer with a polyamide epoxy primer was tried on the USCG Cutter Yankton in 1973 and failed as noted in Part II of Phase I. The Yankton was blast cleaned to remove the failed coating and rust in May 1974. In areas, the polyurethane could not be removed by blast cleaning. Instead, the hull in these areas was reactivated with MEK (ethyl methyl ketone), and a new top coat of polyurethane was applied.

In the areas where the failed coating was removed, a wash primer manufactured by Hughson was applied followed by the Goodyear polyurethane top coat.

The Yankton saw service along the Atlantic Coast near Portland, Maine, during the icebreaking season of 1974 to 1975. Once again, the coating performance was poor, and it failed along the water line of the ship. The polyurethane separated at the interface between the primer and top coat. Changing the primer to the wash primer from the epoxy did not seem to make any difference. It was suggested that the cause of the poor performance was either poor weather conditions or deterioration during service.

ii. USCG Cutter Sauk

The USCG Cutter Sauk was originally coated with the Dexter polyurethane (rigid) in 1973 (see Part II of Phase I). The system consisted of a polyamide epoxy primer and a polyurethane top coat. It appeared to perform quite well, although it was not removed from the water for inspection.

In October 1984, the ship was dry docked, and a complete inspection was performed. The previous observations were confirmed. Approximately 90% of the coating was intact. The only problem areas were at the water line where ice had abraded the coating. The roughness of the coating had increased slightly. The hardness was unchanged, while the thickness changed a maximum of 25 microns (1 mil).

As an added benefit, the coating did not suffer damage from fouling. Barnacles were easily removed, leaving only a slight residue on the coating. The barnacles could not penetrate the polyurethane.

After the inspection was completed, the Sauk was blast cleaned and recoated with a coal-tar epoxy system consisting of the following:

- 51 microns to 102 microns (2 mils to 4 mils) of red lead primer;
- 152 microns to 203 microns (6 mils to 8 mils) of coal-tar epoxy;
- 13 microns to 25 microns (0.5 mils to 1 mil) of vinyl red antifouling.

The bond strength of the antifouling is poor, only 7 bar to 14.5 bar (100 psi to 210 psi). However, it was applied only to prevent marine growth during the time the ship would be operating in ice-free waters.

The results of the coating-system performance were pending at the conclusion of Phase II of the study.

iii. USCG Cutter Raritan

The USCG Cutter Raritan was blast cleaned to white metal and coated with Zebron polyurethane in June 1974. The weather was warm, ranging in temperature from 20°C to 24°C (68°F to 75°F) at relative humidities of 60% to 80%.

The coating was applied 762 microns to 1,016 microns (30 mils to 40 mils) thick over all the hull, except in the bow area where it was applied 2,540 microns (100 mils) thick.

The bond strength of the polyurethane to the hull was 103 bar (1,500 psi), while the primer was 62 bar (900 psi). The type of primer used was not stated.

The Raritan was dry docked for inspection in August 1977 after 600 h of icebreaking service in the Great Lakes near Sault St. Marie. The only areas of damage were isolated patches at the water line near the bow. The patches were each about 0.1 sq m (1 sq ft) in area. It was estimated that 98% of the coating was intact. Below the water line, a few isolated rust spots and areas of coating delamination were noted. It was determined that mismetering of the two-component spray was the cause of the delamination.

The marine fouling that had formed on the hull was primarily weeds and a jelly-like substance. Both were easily removed by water jetting, with no damage to the coating.

The Zebron polyurethane wore near the water line in a band approximately 203 mm (8 in) wide. The worst area was near the bow where the thickness was reduced from an average of 2,286 microns to 1,067 microns (90 mils to 42 mils). Thirty feet from the bow, at the water line, the average thickness was reduced from 1,016 microns to 787 microns (40 mils to 31 mils). Below the water line, there was no reduction in the coating thickness.

The surface roughness of the Zebron polyurethane increased along the water line, but below it, there was no indication of a change. The increase at the water line was from 5.6 microns to 8.9 microns (0.22 mil to 0.35 mil).

Approximately 4.6 sq m (50 sq ft) of hull was repaired by hand mixing and trowelling the Zebron coating onto the surface after blast cleaning and priming. The Raritan was then put back into service for the 1975 to 1976 winter.

iv. USCG Cutter Mackinaw

The USCG Cutter Mackinaw was coated in 1974 with the Hughson polyurethane system. Only one third of the hull was coated due to labour problems and poor weather.

On the starboard side, a wash primer (9924) and Chemglaze II polyurethane were applied 178 microns to 203 microns (7 mils to 8 mils) at the boot top. Below this, the coating system was 89 microns to 127 microns (3.5 mils to 5 mils) thick.

On the port side, the coating system was a wash primer (9924), followed by a polyurethane elastomer and the rigid-polyurethane top coat (Chemglaze II). It was applied 457 microns to 508 microns (18 mils to 20 mils) thick at the boot top and 203 to 305 microns (8 mils to 12 mils) thick on the hull below.

The bond strength of the starboard polyurethane was almost twice as great as the port-side system. The starboard coating system exhibited an adhesion of 60 bar (865 psi). It was also not as elastic as the port-side coating. It could be scratched with an E2 to E3 pencil, while the port-side polyurethane could not be scratched.

The coating systems were applied in late May and early June. The weather was variable, with several days of intermittent rain. The temperature varied from 13°C to 20°C (55°F to 68°F) during the day. The relative humidity averaged about 60% during the day.

The pitting on the hull of the icebreaker was significant. Some coating pits were as deep as 6.4 mm (0.25 in). No filler was used, so that the surface was very rough after coating.

After 600 h of icebreaking service, the coating condition on both sides of the Mackinaw was poor to fair.

On the port side, the elastomer/rigid-polyurethane system was in poor condition. It was completely removed from the top boot down to about the 4.6-m line. Below that, the coating was intact, but heavy rust was showing through the coating. It appeared that the coating was very porous. Where the coating was still intact, there was only 203 microns to 305 microns (8 mils to 12 mils) remaining.

The coating also appeared to have continued curing, or aging, after exposure to the water. The coating could be scratched with a pencil lead between E3 and E4, whereas the original coating could not be scratched due to its elasticity.

The rigid polyurethane on the starboard side fared somewhat better than the port-side polyurethane. It was removed from the water line to 1.8 m (6 ft) below the water. Below this, primer remained in a band 0.9 m (3 ft) in width. From the 2.7-m (9-ft) mark, down to the keel, the polyurethane was still intact. In this area, rust was evident in locations where the tips of surface roughness asperities penetrated the coating. The coating had also been worn away slightly in this area to a thickness of 127 microns to 178 microns (5 mils to 7 mils).

Once again, the polyurethane continued to harden during the year of service. It could not be scratched by any pencil lead; whereas after application, it could be scratched by a pencil lead between E2 and E3.

The Mackinaw's bow area was recoated during June 1975 with the Zebron polyurethane system that was used on the Raritan. The reason for applying it to the Mackinaw was that it had proven to be successful on the Raritan, a small tug, and it was desirable to test it on a larger ship.

The Zebron polyurethane was applied 6.4 mm (0.25 in) thick on the port side of the bow and 2.5 mm (0.1 in) thick on the starboard side.

Further back on the ship, the coating was tapered to 762 microns (30 mils).

In heavily pitted areas, the Zebron was used as a filler material. The process involved the following steps:

- Grit blast clean the hull to a commercial blast;
- Clean with toluene and prime (less than 25 microns [1 mil] thick);
- Apply the Zebron polyurethane by spray, and squeegee the coating into the pits;
- After curing, grind the high points off the coating until a uniform surface is achieved;
- Clean all surfaces with toluene, and apply by spray the top coat of Zebron polyurethane;
- Touch up any rough areas with a hand-mix material by trowelling.

No filler material was added to the Zebron polyurethane because of its high viscosity. The material could be applied in heavy layers without sagging or running.

The temperature during the application in the dry dock varied between 17°C and 26°C (63°F and 79°F). The humidity varied between 50% and 70%. Conditions were generally very good.

The bond strength of the Zebron to the steel was very high. The primer exhibited a bond strength of 119 bar to 133 bar (1,725 psi to 1,925 psi). The polyurethane top coat had adhesion strengths slightly lower at 105 bar to 106 bar (1,530 psi to 1,545 psi).

The results of the coating performance after several years ice service are detailed in Phase III of the USCG study.

v. USCG Cutter Westwind

The USCG Westwind was coated with the Baltimore glass-flake polyester in June 1974. This coating was not one of the original products subjected to the laboratory tests. It had, however, been used on an icebreaker and, therefore, was of interest.

The coating was applied 889 microns to 1,016 microns (35 mils to 40 mils) thick.

After approximately 700 h of service in the Great Lakes and the Arctic, it was dry docked in November 1975. Inspection indicated that the condition of the coating was fair.

In the bow area, 50% to 60% of the coating was removed. The remaining coating on the hull varied in thickness from 152 microns to 1,016 microns (6 mils to 40 mils).

A band of coating 1.2 m to 2.7 m (4 ft to 9 ft) wide was removed from the water-line area on either side of the bow. The width tapered to less near midships.

Below the water line, the coating showed heavy rusting through it, and it was evident that water penetrated the coating to the steel hull. These were primarily areas where the coating was very thin (less than 127 microns). The coating also showed wear in areas far below the water line. Isolated patches near midship were less than 305 microns (12 mils) thick. This suggested that wear was occurring from ice sliding beneath the hull. The polyester coating wore on areas of the hull that the polyurethane and epoxies did not wear.

The hardness of the polyester coating increased during service in the water. It was found to be harder than any of the polyurethanes or epoxies previously tested. An E5 pencil lead would not scratch the polyester that remained on the hull.

In addition, the ship's operators did not notice a reduction in resistance with the hull coated. This suggests that the frictional properties of the polyester-coated hull were not significantly lower than a bare-steel hull. The laboratory tests had shown that the glass-flake polyester coatings did not significantly improve the frictional properties of the steel on ice because of the coarse nature of the glass-flake particles. Therefore, the full-scale test results made sense.

(c) Conclusions

The conclusions of the full-scale testing program on the USCG icebreaker fleet were as follows:

- Solvented elastomeric coatings, such as the Goodyear and Hughson polyurethanes, give poor results as a hull coating for an icebreaker;

- Solvented rigid polyurethanes give fair to good results, except in areas of maximum wear (bow and water line);

- The nonsolvented polyurethane (Zebron) produced the best results. The areas of damage were restricted to the bow and water line;

- Bond strengths of approximately 103 bar (1,500 psi) are needed for a coating to withstand icebreaking service;

- The nonsolvented polyurethane's performance suggested that the hull resistance was reduced compared to that of bare steel;

- Fouling is easily removed from low-friction hull coatings, particularly from the polyurethanes;

- The nonsolvented polyurethane could be used without a filler to fill in the corrosion pits;

- The areas of greatest wear are at the bow and the water line.

3. USCG Study - Phase III (1976 - 1978)

Phase III of the study examined the following areas in the research program:

- Full-scale resistance tests;
- Full-scale coating tests (continued from Phases I and II);
- Fouling characteristics of the coatings;
- Practicality of partial hull coatings;
- Environmental parameters for coating application;
- Economic benefits of hull coatings;
- Laboratory tests on hull coatings (continued from Phases I and II).

(a) Full-Scale Tests

The first series of tests were full-scale resistance tests in ice on two sister ships, the USCG Cutters Raritan and Arundel.

The Raritan was coated with Zebron, a nonsolvented polyurethane, while the Arundel was coated with a bituminous epoxy. Both ships had been coated approximately two years prior to the tests.

Prior to the actual tests, each ship was "tuned up" to ensure that both ships' amperage, voltage, and shaft speed were identical at each step. A calibration curve was then established in open water for thrust versus shaft speed. A strain-gauged load cell was used to measure thrust while monitoring the shaft rpm. The cell was then set in series with a hawser line tied to the towing bollard between two ships or between the ship and a dock bollard. Shaft speed was monitored using a magnetic probe sensor and a light probe. Both signals were recorded on a strip-chart recorder.

Tests were conducted in both brash (floating ice less than 2 m [6.6 ft] across) and a solid, sheet-ice field. However, the results from the solid sheet ice were inconclusive because the ice had begun to decay.

The brash-ice tests were conducted in Saint Marie River Channel. Both ships travelled in the same direction adjacent to each other. However, they "hopscotched" their runs so that each ship could proceed through undisturbed brash ice without interference from the other ship.

The results indicated that the Raritan (Zebron coated) gave an 8% reduction in power required at 3.0 kn (3.5 mph) and a 15% reduction at 6.0 kn (6.9 mph) over the Arundel (bituminous epoxy).

Both ships were also asked to proceed through the ice field at the lowest possible power step. The Raritan proceeded through the field at Step 5, while the Arundel had to use the 7th step.

It was concluded that the polyurethane produced a lower resistance to ice than the bituminous epoxy.

Full-scale tests were continued on several icebreakers involving the Zebron polyurethane and the Inerta 160 epoxy. The Zebron polyurethane had originally been tested in Phase II on the USCG Cutters Raritan and Mackinaw. It performed exceptionally well on the Raritan.

On the Mackinaw, the Zebron polyurethane was applied to the bow area and the water-line area, 21.3 m (70 ft) from the bow. This was described in detail in Phase II of the study. After 1,100 h of icebreaking service, the hull was examined. Most of the 3-m (10-ft) wide strip near the boot topping had been removed, except for small areas of coating in the lower 0.6 m (2 ft) of the strip.

Beneath the boot topping, the coating was still intact and in good condition. In the bow area, it was almost totally intact. Where there were areas of failure, the top coat appeared to be delaminating from the bottom coat. Two coats had been originally applied to the hull. The first coat was applied by spray and squeegeed into the corrosion pits. The second coat was applied a day later by spray. The cause of the failure was thought to be mismetering in the spray gun (improper mix ratio of the catalyst and base)*.

In 1976, the Zebron polyurethane was applied to the Alaskan Husky, a 42.7-m (140-ft) icebreaker, to test the performance of filled versus unfilled polyurethane. The port side was coated with the amorphous silica-filled polyurethane, while the starboard side was coated with the unfilled product.

The coatings were applied in Seattle in May, when weather conditions can be unsettled. A tent was constructed around the hull, and four propane heaters were used to heat the enclosure. No details were given regarding the temperature or humidity inside the shelter.

At the conclusion of the Phase III report, the Alaskan Husky had not been dry docked. However, it was inspected while in the water, and most of the damage appeared to be at the bow and stern ice line. Below the ice or water line, the coating was intact, except for several small areas subject to hard contact during docking. It was concluded that after 1-1/2 years service, the coatings were protecting the hull. No discernable difference was noted between the performance of the filled and unfilled polyurethane.

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*The authors have observed a similar occurrence on steel piling coated with Zebron.

Full-scale tests were continued on the USCG Cutter Glacier. A putty had been tried as a filler for corrosion at weld areas, but ice had removed most of the filler during service. It was decided to fill the welds with nonsolvented coatings. The Zebron polyurethane was applied on the starboard side of the ship (1.5 m [5 ft] to 22.2 m [73 ft] from the bow) from the boot top down to within 2.1 m (7 ft) of the keel. The Inerta 160 epoxy was applied on the bow and the port side to a distance of 21.3 m (70 ft) from the bow. The area covered was from the boot top to the keel.

At the time of the report, the Glacier had not been dry docked, and therefore, the preliminary examination of the coatings was conducted while the ship was in the water. After 168 h, small areas of the Zebron had delaminated. The coating had been applied in two coats, the first being the filler coat. The cause of the delamination was not known. It was suggested that mismetering or application of the second coat after the first coat had cured was the cause. Other than these small areas, the Zebron polyurethane appeared to be in good condition.

There appeared to be no damage to the Inerta 160 epoxy, but because the coating could not be inspected at close range, it was not definite.

The Inerta 160 epoxy was also tested on the USCG Cutter Ojibwa. In October 1976, it was coated at Sturgeon Bay, Wisconsin. A polyethylene shelter was constructed around the hull because it allowed the work to be completed in one day. Had a shelter not been used, the work would not have been completed for at least one week. Dry-dock costs were $5,000 (U.S.) per day, so that the shelter more than paid for itself.

The temperature and humidity within the shelter were 16°C (60°F) and 55% to 85%, respectively. The steel temperature was 13°C (55°F) inside the shelter. The temperature outdoors was -1°C (30°F) at the time of work, with heavy snow. Four industrial heaters were used to heat the tent.

The Inerta 160 was applied to a thickness of 559 microns to 838 microns (22 mils to 33 mils) on the boot topping and 457 microns to 635 microns (18 mils to 25 mils) below this area. No primer was used.

After 358 h of icebreaking service, the total coating damage was less than 2%. Coating was removed from an area that was coated by brush, rather than spray. There were also heavy scratches on the coating.

After 900 h of icebreaking, the coating was 95% intact. The major areas of damage were at the bow, stern, and near the rudder.

A major advantage noted by the ship's commanding officer was that the ship did not become lodged in the ice as easily as the ship did prior to applicaton of the Inerta 160. Other ships (not coated with the Inerta) working in the same area became stuck much more easily.

The authors of Phase III of the study also visited the Wartsila shipyard in Turku, Finland, to inspect the Inerta 160 coating on the Finnish icebreaker, Karhu I. After 800 h of service in ice, the coating was 90% intact. The 10% coating damage was randomly distributed throughout the hull surface. Corrosion was evident below the water line as the top of asprities and in weld areas.

As an experiment, two coats of Inerta had been applied in one area of the hull. The second coat had delaminated from the first coat because of a white scum that formed between the two layers. The scum was formed by the absorption of carbon dioxide by the amine component of the epoxy. Carbon dioxide will react with moisture to form a barrier between coats.

After completion of the full-scale tests, it was concluded that both the Zebron polyurethane and the Inerta 160 epoxy significantly improve the corrosion resistance of the icebreaker hulls and will survive several years of icebreaking service without substantial damage.

(b) Marine-Fouling Tests

To test the fouling characteristics of the Zebron polyurethane, test panels coated with the Zebron were placed in seawater at the Long Beach Navy Yard and the Battelle Marine Facility in Daytona, Florida. The panels were examined after several months in the water. The Zebron had no antifouling capabilities because all samples fouled with barnacles and weeds. However, after removal of the fouling by brushing, no damage was noted on the Zebron coating. There was no change in thickness after 17 months exposure.

To test the adhesion of the Zebron, a panel coated with the Zebron was scribed with a line. Barnacles lodged themselves in the scribe mark, but penetration under the coating was less than 1.6 mm (0.06 in). This is important, since most conventional coatings will disbond once the adjacent surface is exposed to corrosion and fouling.

The importance of the resistance of the Zebron polyurethane in withstanding damage from fouling and removal of the fouling should not be underestimated. A coating that can be cleaned without being damaged could be cleaned by underwater techniques which utilize vigorous brushing action. Removing the fouling by this method not only saves money by reducing dry docking costs, but it also reduces fuel costs. A clean hull could reduce fuel costs by 25%.

(c) Laboratory Tests

Laboratory tests continued in Phase III of the study to establish the environmental parameters of the most promising coatings and bond characteristics of the coatings. In addition, new materials that were not previously evaluated were tested.

To evaluate the environmental parameters of the Zebron polyurethane and the Inerta 160 epoxy, blast-cleaned steel plates were coated in a chamber in which the temperature and humidity could be controlled.

The two coatings were applied under the following conditions:

TEMPERATURE (°C)	RELATIVE HUMIDITY (%)
-12	10
- 1	10
- 1	30
10	10
10	30
10	60
21	10
21	30
21	80

The Zebron-coated plates were first coated with a vinyl phenolic primer. The Inerta 160 had no primer.

After application of the coating system under the stated conditions, the coatings were allowed to cure overnight at -9°C (15°F) and a humidity of 10%. After 15 h, they were cured at 4°C (40°F) and 60% relative humidity for 24 h. The specimens were then removed from the chamber and allowed to cure at 21°C (70°F) and 45% humidity. To test for final cure, the coatings were tested with an E4 pencil lead. If they could not be scratched, it was assumed that a final cure had been reached.

The adhesion of the samples was then tested. It was found that application temperature had very little effect on the Inerta 160 epoxy, while the adhesion of the Zebron improved slightly as the temperature increased. The weak link in the Zebron system was the primer. Most failures were adhesive failures at the primer. The bond strength of the Zebron system ranged from 97 bar to 124 bar (1,400 psi to 1,800 psi).

The failures in the epoxy system were usually cohesive in nature. The bond strength of the Inerta 160 epoxy ranged from 62 bar to 83 bar (900 psi to 1,200 psi).

The test indicated that the Zebron polyurethane would cure at lower temperatures than the epoxy. At 4°C (40°F), the Zebron cured, while the Inerta 160 remained viscous. In addition, condensed moisture on the cold-coated surface did not adversely affect the cure or the final hardness of either coating.

The bond strength of an antifouling coat to a high-performance coating was tested. Usually, an antifouling coat has a bond strength of 5 bar to 21 bar (70 psi to 300 psi) to a corrosion-resistant coating. It is usually applied after the corrosion-resistant coating has dried, otherwise solvent would be trapped or would form bubbles in the antifouling coat. With the Zebron polyurethane, the antifouling can be applied while the Zebron is still wet because the Zebron is solventless. As a result, a chemical bond develops between the Zebron and the antifouling coating. This bond increases the adhesive strength of the antifouling coating to the Zebron. The bond strength was 66 bar to 79 bar (955 psi to 1,145 psi).

When applying a second coat of a high-performance coating to a first coat, a good bond may not be obtained. During the Phase III laboratory tests, three methods were tested as follows:

- Apply a second coat to a previously cured coat of Zebron;
- Apply a second coat while the first coat of Zebron is still wet;
- Mechanically abrade the first coat prior to applying the second coat of Zebron.

The highest bond strength was developed when the second coat was applied while the first coat was still wet. Strengths were in the order of 115 bar to 126 bar (1,670 psi to 1,820 psi). A chemical bond forms between the two coats when this method is followed. Failure does not occur at the interface between the two coats.

By abrading the surface of the first coat of Zebron, bond strengths of 79 bar to 93 bar (1,150 psi to 1,350 psi) are attainable. Failure is associated with the interface between the two coats of Zebron.

The weakest bond attainable occurs with no surface preparation between the fully cured first coat and the subsequent coat. Bond strengths of only 47 bar to 65 bar (687 psi to 940 psi) result, and failure occurs at the interface.

These tests point out the importance of the surface condition of the first coat in reapplying high-performance coatings. To increase the thickness of a high-performance coating, a subsequent coat should be applied while the previous coat is still wet. In repairing existing coatings that have been in service for several years, the coating must be mechanically abraded prior to application of the repair coat.

In the previous phases of the study, the Inerta 160 epoxy never underwent the laboratory tests used to screen the vast range of coatings that were tested. Phase III subjected several coatings and new materials to the long-term wear test, the ice-crushing resistance test, and frictional analysis.

The long-term wear tests were performed as detailed in Phase I of the study. Two new coatings were tested, Inerta 160 and Woolsey Marine W2 epoxy. For comparison, tests on silica-filled and unfilled Zebron were run.

The W2 epoxy gave very poor results. The coating spalled at the edges and in the middle. The surface roughness increased from 1.5 microns CLA to 3.2 microns CLA (0.006 mil to 0.13 mil).

The Inerta 160 epoxy was completely intact after 840 h of testing, but at the end of 1,320 h, the coating had worn through. It was concluded that once the Inerta 160 starts to wear, the wear rate increases drastically until the steel substrate is exposed.

In comparison, the Zebron polyurethane exhibited very little wear, with only 38 microns to 51 microns (1.5 mils to 2 mils) of coating lost from asperities.

Despite the poor results on the Inerta 160 epoxy from the wear test, it withstood the crushing-ice resistance test. No apparent damage resulted from the test.

With the friction tests, the Inerta 160 showed the following behavior:

- Breakaway coefficient: 0.25 to 0.32;
- Static coefficient: 0.21 to 0.25;
- Kinetic coefficient: 0.08 to 0.09.

Compared to the Zebron test results obtained in Phase II, the coefficients were lower for the Zebron polyurethane. The breakaway coefficient for the Zebron was 0.11 to 0.12, the static coefficient was 0.10 to 0.11, and the kinetic coefficient was 0.03 to 0.04.

It was concluded that the Inerta 160 epoxy was the best coating of the new materials tested, which included another unsolvented epoxy (Aquacoat 28.05), a glass-filled epoxy and copper cladding.

To date, all test specimens used in the study were prepared from new steel. To simulate the actual surface of a corroded hull, plating was obtained from a U.S. Coast Guard yard in Maryland. Frictional-resistance tests were performed on both coated and uncoated steel hull plating. By coating the steel with the Zebron polyurethane, the static friction coefficient was reduced from 0.82 to 0.23. The kinetic friction coefficient was reduced by 0.06 to 0.07. It was concluded that a high-performance coating will significantly reduce the frictional resistance, even on a very rough hull plate.

The final test conducted in the study involved partial hull coatings. It is considerably less expensive to apply a high-performance coating to only those areas of the hull subject to the most severe ice abrasion than applying it to the entire hull. The study concentrated on identifying those areas and the minimum surface area required to gain a significant reduction in resistance.

A model icebreaker was built, and the hull was coated with cream car wax to identify the areas of highest abrasion. The model was then towed through a tank of ice. The hull was then examined in those areas where the wax was rubbed off by the ice.

The primary finding in these tests was that the use of as little as 10% low-friction, abrasion-resistant coating significantly reduced frictional resistance. The beneficial effect increased up to 20% coated area. Above 20%, little additional benefit was obtained. This applies to lower frictional resistance and power reduction. It does not refer to corrosion protection.

The areas of the hull that should be coated are the bow and the water line from the bow to midship. It was stated that these areas are several hundred times more important in the frictional resistance of the hull than the bottom of the ship.

(d) Economic Analysis

To conclude Phase III of the study, an economic analysis was performed on several ice-going vessels coated with the high-performance coatings. Included in the analysis was the USCG Cutter Glacier.

The Glacier is an existing ship that had undergone extensive weld repair between 1971 and 1979, averaging $128,000* for each dry docking (two-year intervals). A decision was made to coat the hull with a high-performance coating at an initial cost of $80,000.

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*1974 U.S. dollars.

To analyze the economics, the coating repair cost was assumed to be $16,000 for each subsequent dry docking. At two-year intervals, the total cost of coating the Glacier and maintaining the coating would be $144,000 for an eight-year period ending in 1987. Compared to a cost of $640,000 for weld repair during the same period of time (assuming $128,000 per dry docking at a two-year dry-docking interval), the cost savings are substantial. Nearly half a million dollars could be saved by coating the hull. This does not include cost savings generated for reduced fuel consumption caused by the decrease in frictional resistance.

If it is assumed that the price of oil remains constant at $13.50 per barrel, the discount rate is 10%, and the resistance in open water is reduced 10% and in ice by 30% (for an old ship), the cost saving over a 12-year period is $293,742. This saving results from the reduced frictional resistance.

It can be concluded that the cost savings are substantial when a high-performance coating is applied to an icebreaker hull. The initial cost of applying the coating can be offset by a very small reduction in resistance of only 2% for open water and 6% for ice. Even ships with a short economic life require a reduction of only 5% and 15%, respectively, to make it economically viable to coat the hull. This study, and others, has shown that reductions of as high as 14% are possible in open water and 25% in ice.

(e) Conclusions

The conclusions reached in Phase III of the study are as follows:

- To protect an icebreaker hull from corrosion, a nonsolvented, high-performance coating system should be applied. The Zebron polyurethane survived four years of icebreaking service and was 90% intact. The Inerta 160 epoxy was 95% intact after 1-1/2 years service;

- A significant reduction in resistance occurs when a low-friction hull coating is applied. Both full-scale and laboratory tests showed this to be true;

- Applying the coating to only 20% of the hull (bow and ice-line areas) reduces the resistance significantly;

- The most effective application method for reducing surface roughness of a corroded hull is by spraying, squeegeeing, and reapplying the coating to the hull;

- The restrictions on application conditions for applying the Zebron polyurethane are less rigorous than for the Inerta 160 epoxy;

- The coatings do not possess antifouling characteristics, but fouling organisms can be easily cleaned from the surface without damaging the coating;

- An antifouling coat can be applied to the Zebron polyurethane while it is still wet. Bond strengths between the Zebron and the antifouling coat are very good;

- High-performance hull coatings can significantly reduce operating and maintenance costs on a ship.

4. Finland and Russia

For a good portion of every year, the coastal areas of Finland are locked in ice-covered waters. In some of the more remote communities, the only means of transporting supplies is by ship. This means that the supply vessels must be strengthened for navigation in ice, or they must be accompanied by an icebreaker.

The Finnish Board of Navigation operates a fleet of ten icebreakers. The icebreakers are used to assist the transport vessels through the ice.

The cost of fuel and maintenance on these ships is high. A rough, corroded hull increases the resistance when travelling through ice and necessitates hull repairs at corroded welds during each dry docking.

Conventional hull coatings had been tried on the icebreakers, but they would wear off after only a few hours of ice service. As a result, a research program was initiated by the Wartsila Shipyard, Teknos-Maalit Oy, and the Finnish Board of Navigation to improve the performance of ships travelling in ice-covered waters.

Wartsila had constructed 44 icebreakers as of 1981. This represents 60% of all the large icebreakers in the world. In addition to these vessels, they have constructed numerous large passenger ferries and commercial ships which regularly travel in ice-covered waters. Silja Line and Finnjet operate large car/passenger ferries that travel between Finland and Sweden. These ferries typically carry over 1,000 passengers, making several trips per week between Helsinki and Stolkholm year round. Since many of the ships constructed at Wartsila will operate in ice, the shipyard established the Wartsila

Arctic Design and Marketing Department (WADAM) in 1974 to concentrate on research and development for icegoing ships.

WADAM's primary aim is to serve the projects of Wartsila and improve designs prior to production. This includes mapping ice conditions on all ice-bound shipping routes, full-scale performance tests of constructed vessels, and model tests in the laboratory.

Ice-property studies are performed in an icebreaking model test basin. The studies included phenomena similar to the USCG study at the Rensselaer Polytechnic Institute. Mechanical friction and friction coefficients between ice and steel were examined. The studies revealed that the quality of ice, snow, and the surface of the hull influenced the frictional coefficients. The type of contact between the ice and the hull determines the normal force. Figure III-2 illustrates the different types of contact. Part A) shows the types of contact that occurs at the bow when level ice is broken. The action is frictional forces combined with impact. Part B) is friction between the side of the ship and ice. Part C) shows the normal force due to buoyancy only. Part D) illustrates a ship in an ice ridge where contact is made with numerous blocks of ice. The forces exerted on the hull are frictional, impact, and buoyancy.

Their studies indicated that the frictional part of the ice resistance could not be explained by the means of one value for the dynamic (kinetic) coefficient of friction. To determine the actual friction coefficient on a hull, individual coefficients for each type of contact would have to be measured and integrated over the entire hull. This is impossible to measure. Instead, WADAM performed simple tests to determine frictional coefficients by pulling specimens of hull plate on different types of ice and by pulling blocks of ice on hull plate.

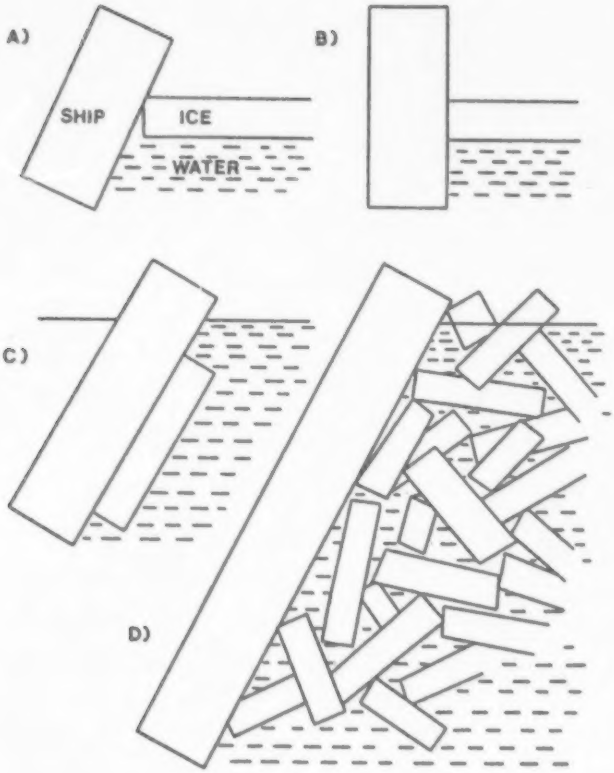

A)
SHIP
ICE
WATER
B)
C)
D)

FIGURE III-2 - VARIATIONS IN CONTACT BETWEEN ICE AND SHIP'S HULL

The values obtained for the kinetic coefficient of friction were as follows:

- Old hull:	0.24;
- New hull with conventional coating:	0.16;
- New hull with special coating:	0.08.

In March of 1973, a series of tests were conducted in the Gulf of Finland near Helsinki with a small icebreaking tug, the MS Jelppari, of Wartsila shipyard. The tests measured the total resistance of the hull as a function of ship speed. The original corroded hull was compared to stainless-steel plating along the water line from the bow to midship. The tests showed the stainless-steel plating to reduce the resistance of the ship at speeds of 1.5 m/s (3.4 mph) or less. The reduction in resistance was larger from 0 m/s to 0.5 m/s (1.1 mph) than at higher speeds. This was due to the high value of the static friction coefficient associated with rough, corroded steel surfaces.

Specimens were then cut out of the ship's hull, and the dynamic coefficient of friction was measured for both the corroded steel and stainless steel versus different types of ice. The coefficient of friction for the stainless steel was less than 0.10. For the corroded steel, the coefficient varied from less than 0.10 to 0.34.

In 1972, the Finnish Coast Guard participated with Wartsila in staging hull resistance tests on two cutters: the MS Silma and the MS Valpas. The hulls of both vessels were bare. The only difference between the two was the condition of the hull. The Silma was nine years old, and the hull was considerably rougher than the Valpas, which was only two years old.

The ships were tested in the same day in an ice field with an ice thickness of 35 cm (13.8 in). The ice-resistance values were measured and plotted on the graph shown in Figure III-3.

The ships were then dry docked in the summer of 1973. The Valpas was coated with a conventional hull paint, while the Silma was coated with a solvent-free epoxy.

In the winter of 1974, both ships were tested in an ice field in the Gulf of Finland. Ice conditions were similar to the tests conducted in 1972, so that comparisons could be made.

The results of the tests were interesting. In 1972, the hull resistance of the Silma was considerably higher than the Valpas. After the solvent-free epoxy was applied, the hull resistance was reduced substantially on the Silma. In comparison, the hull resistance of the Valpas increased. The conventional coating was worn away, and the hull had continued to corrode. The epoxy coating on the Silma was undamaged by the ice.

After completion of the first full-scale tests revealed the importance of low-friction hull surfaces, research was conducted to find a material that would not wear off in ice.

The Finnish icebreakers were usually coated with a bituminous or chlorinated rubber coating to provide corrosion protection to the hull in open water during the off season. However, once ice service began, the coatings would quickly wear away; therefore, the hull steel would be exposed to corrosion for the entire winter. The areas of worst corrosion on the icebreakers is shown in Figure III-4. The shaded areas correspond to the areas with the heaviest corrosion and the most severe ice abrasion. In the other hull areas, corrosion is not as severe because the paint is able to adhere to the steel longer.

In the summer of 1973, laboratory ice-abrasion resistance tests began on the following coatings:

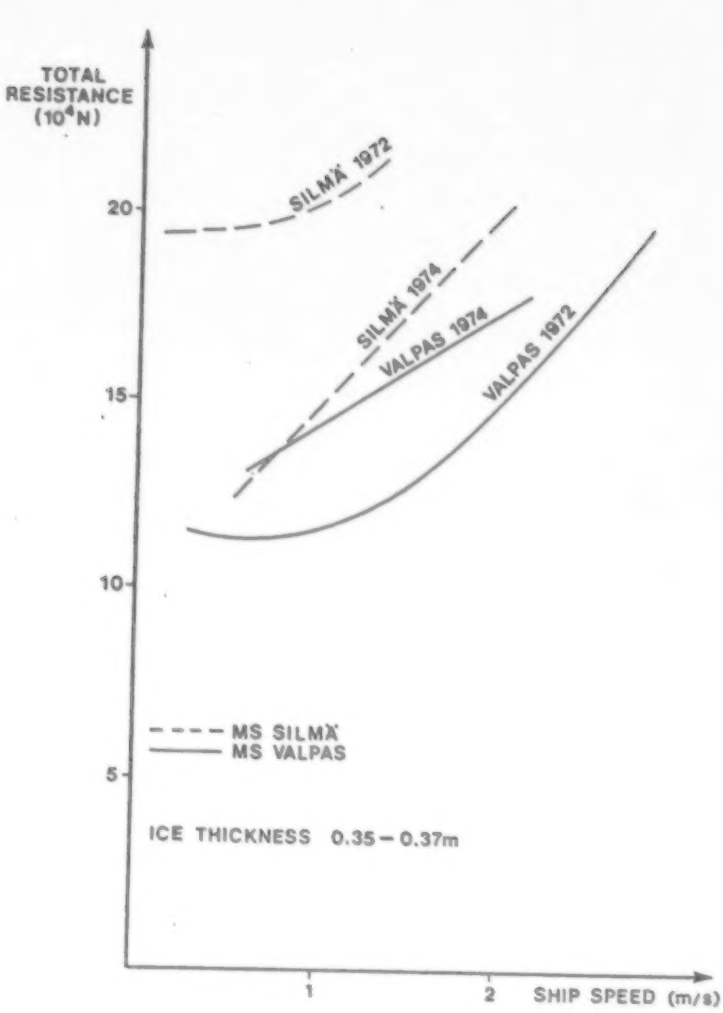


FIGURE III-3 - INFLUENCE OF HULL CONDITION ON RESISTANCE IN ICE-COVERED WATERS

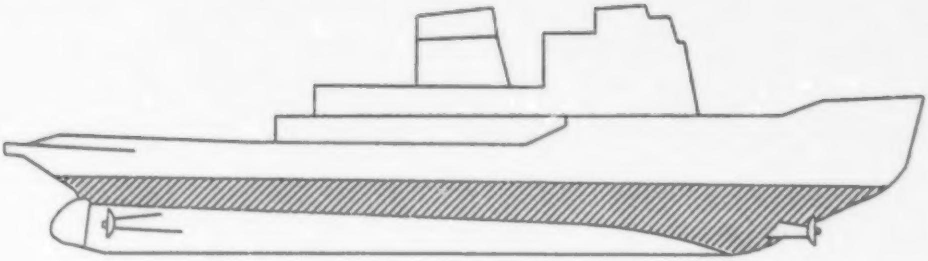


FIGURE III-4 - AREA OF WORST CORROSION AND ICE ABRASION ON AN ICEBREAKER

- Bituminous paint;
- Chlorinated rubber;
- Glass-fibre-reinforced epoxy;
- Metal-sprayed zinc.

The tests were performed on coated steel plates that were rotated on ice at a velocity of 2.0 m/s (4.5 mph), with a pressure of 2×10^5 Pa (29 psi). The temperature was -18°C (0°F).

The bituminous paint and the chlorinated rubber suffered 10% damage after only 1 min. Both appeared to be very brittle, with poor adhesion to the steel.

The epoxies performed very well, with only minor damage after 10 h. The reinforced epoxy seemed to be too rigid for a hull coating because the ice tended to delaminate an entire layer of coating from the steel.

The metal-sprayed zinc performed poorly. The zinc separated from the steel. This was caused by frictional heat producing a thin layer of water on the ice, which subsequently penetrated the pores of the coating, froze, and separated the zinc from the steel.

In the autumn of 1973, full-scale tests began on the hulls of two icebreakers: the Murtaja, a Finnish icebreaker, and the Jermak, a Soviet icebreaker built by Wartsila. It should be noted that much of the Russian experience with coating technology on icebreakers is linked to the research performed in Finland. Joint ventures are commonplace.

Seven coating systems were tested on the two vessels, including a polyurethane system that had undergone laboratory tests by the USCG. The coatings tested are detailed in Table III-2.

After 900 h of ice service, the coating patches were inspected on the hull of the Murtaja. The coal-tar epoxy primer systems, the polyurethane/epoxy primer system, and the

TABLE III-2

COATINGS EVALUATED FOR ABRASION RESISTANCE TO ICE ON THE MURTAJA ICEBREAKER

COATING SYSTEM	NO. OF COATS	THICKNESS	
		MICRONS	MILS
Zinc-Silicate Primer	1	600	2.4
Coal-Tar Epoxy	2	220	8.7
Coal-Tar Epoxy	2	220	8.7
Epoxy Smoothing Compound	1	>1,000	>39.4
Coal-Tar Epoxy	2	220	8.7
Solvent-Free Coal-Tar Epoxy	1	400	15.7
Epoxy Smoothing Compound	1	>1,000	>39.4
Solvent-Free Epoxy	2	1,000	39.4
Zinc-Silicate Primer	1	60	2.4
Epoxy	2	---	
Epoxy Primer	1	70	2.8
Polyurethane	2	240	9.4

epoxy/zinc-silicate system did not withstand the service in ice. The coatings were at least 50% damaged in all cases. The coal-tar epoxies became brittle in the cold weather.

The only coating able to withstand the test was the epoxy smoothing compound and the solvent-free epoxy. No damage was noted on the epoxy.

The icebreaker Jermak was inspected in January 1975 while still in the water with the water-line area visible for inspection. The results were similar to the Murtaja. The only coating remaining on the hull was the solvent-free epoxy manufactured by Teknos-Maalit Oy under the name Inerta 160.

As a result of these tests, the Inerta 160 was applied to the hulls of six Soviet river icebreakers. These icebreakers are in the Kapitan Chechkin class, which has a shallow draft to allow them to operate in river estuaries. The river environment in which these icebreakers operate is severe because the coatings must not only withstand abrasion from ice, but also large amounts of sand and other foreign objects.

In 1981, comparative tests were run between the Kapitan Dranitsyn and the Kapitan Nikolaev in the estuary of the river Yenisei. The thickness of the ice in the river was 1.45 m (4.8 ft), with a snow cover of 0.30 m (1 ft). The Nikolaev was not coated with the Inerta 160, and it had a resistance 17% higher than the Dranitsyn.

In 1983, the nuclear-powered icebreaker, Rossiya, was constructed by Baltiysky Shipyards in Leningrad. The hull was coated with Inerta 160.

In Finland, the Lunni class icebreaking tanker has been in service since 1976. The main task of the tankers are to carry petroleum products from the refineries in the south to the towns on the Finnish coast and to transport crude oil from the Baltic to the refineries in Finland.

The ships were designed to operate in ice without icebreaker assistance, unless conditions were severe. The hull design took into consideration icebreaking capabilities. It was strengthened and coated with Inerta 160 epoxy.

The Inerta 160 has reduced the ice resistance by about 10% and coating wear has been good. Only minor repair work has been required on the epoxy.

As mentioned previously, ferry vessels have also been coated with the Inerta 160 epoxy. The MS Turella operated between Finland and Sweden. It has demonstrated a fuel saving of 7.1% after being coated.

5. Other Countries

Investigations have not revealed any other sources where significant work was completed in the area of coatings suitable for service in ice. Some work has been completed in Canada and other Scandinavian countries, such as Denmark, but the bulk of the research appears to have been concentrated in the United States and Finland.

Canadian National Railways operates coastal vessels and ferries in the waters off Newfoundland. In 1966, R.P. Rennie and M.J. Turnbull studied several protective coatings on hulls of ships including vinyls, asphaltics, coal-tar epoxies, and chlorinated rubbers(35). No success was realized because ice action removed the coatings in only a few days.

In Denmark, Hempel Marine Paints Inc. developed a solvent-free epoxy for ice service in 1976. However, widespread application did not commence until 1980.

D. SPECIFIC COATINGS

1. International Paints' Inerta 160

The Inerta 160 was the first high-performance coating to succeed in full-scale tests on icebreakers. It has probably gained the greatest use worldwide of the solventless coatings. By 1983 Inerta 160 had been applied to over 300 icegoing vessels. A partial list of the coating applications is attached in Appendix I.

The Inerta 160 is a two-component, high-solids, epoxy-resin-based coating with good adhesion to blast-cleaned steel and excellent abrasion resistance. Table III-3 details the properties of Inerta 160.

Inerta 160 stopper is used as a filler material on pitted steel hulls. It consists of epoxy and inert fillers and extenders. It is sprayed onto the pitted steel surface after blast cleaning and then spread into the pits with a broad putty knife. The Inerta 160 coating is then applied over top of the stopper material.

Inerta 160 also exhibits good chemical resistance to oil, grease, and petroleum products. However, strong solvents will cause the coating to swell.

2. Reliance Universal Zebron 1864

The Zebron polyurethane originally was marketed in the early 1970s under the trade name of Crandalon. The USCG study by S.J. Calabrese tested the Crandalon nonsolvented polyurethane in Phase I and the Zebron polyurethane in Phases II and III. The major difference between the two products was that the Crandalon coating had an amorphous silica as a filler.

The product marketed by Zebra Coatings from the late 1970s to 1982 was known as Zebron 385-3, 385-5, and 386-4, depending upon whether application was by spray, roller, or brush. Zebron 386-4 was used on the hulls of most ships. It could be applied with or without a primer.

In 1982, Zebra Coatings began marketing Zebron (TM) 1864 polyurethane. It is essentially the same coating as

TABLE III-3

INTERNATIONAL PAINTS

COATING SYSTEM

PROPERTY	INERTA 160 STOPPER	INERTA 160
Generic Type	High-solids, two-component, epoxy fill.	High-solids, two-component, epoxy fill.
Solids By Volume	96 ± 1%	97 ± 2%
Mixing Ratio (base to catalyst)	2 : 1	2 : 1
Dry-Film Thickness	500 microns	750 microns
Surface Preparation	Sa 2-1/2	Sa 2-1/2 80-micron profile
Dry to Touch	8 - 10 h @ 25°C	5 h @ 25°C
Ultimate Cure	7 days @ 15°C or 4 days @ 25°C	7 days @ 15°C or 4 days @ 25°C
Recoating Time		
Minimum	1 h @ 25°C	5 h @ 25°C
Maximum	16 h @ 25°C	24 h @ 25°C

Zebron 386-4, except that a primer is not used with the product (see Table III-4).

In 1983, Zebron (TM) 1864 was tested by S.J. Calabrese of the Rensselaer Polytechnic Institute for Zebra Coatings. It was found that the properties of the Zebron (TM) 1864 were at least as good as the original Zebron with a primer(36).

In 1985, Zebra Coatings was sold to Reliance Universal Inc. Reliance now possesses the licence for marketing the product in Canada and the United States. Zebra S.A. markets the product elsewhere in the world.

The Zebron coating is a solventless, two-component polyurethane. It is 100% solids, whereas the Inerta 160 is slightly solvented. It possesses good abrasion-resistance properties and can be applied to thicknesses approaching 5.0 mm (0.2 in) using a wet-on-wet spray technique.

It also possesses shorter drying and curing times than the Inerta 160 epoxy.

A list of coating applications using the Zebron products on the hulls of ships is included in Appendix I.

3. Hempel's Marine Paints Hempadur 3555

Hempadur 3555 was first introduced onto the market in 1976, but most of the commercial applications did not begin until 1980 (see the coating application list in Appendix I).

The coating is a solventless, two-component polyamine-cured epoxy highly resistant to abrasion and impact. It is also chemically resistant to mineral oil, aliphatic hydrocarbons, and alkaline and mild acid solutions.

The coating is similar to the Inerta 160 in that both are epoxies, but the Hempadur 3555 is solvent-free. Properties of the Hempadur 3555 are detailed in Table III-5.

TABLE III-4

RELIANCE UNIVERSAL
COATING SYSTEM

PROPERTY	ZEBRON 386-4	ZEBRON (TM) 1864
Generic Type	Nonsolvented, two-component, polyurethane.	Nonsolvented, two-component, polyurethane.
Solids By Volume	100%	100%
Mixing Ratio (base to catalyst)	3 : 1	3 : 1
Dry-Film Thickness	750 microns (minimum)	1,000 microns
Surface Preparation	Sa 2-1/2 75 micron profile	Sa 2-1/2 75-micron profile
Dry to Touch	30 min @ 25°C	
Ultimate Cure	7 days @ 15°C	
Recoating Time		
Minimum	---	
Maximum	---	
Additional Notes	The Zebron 386-4 could be used with A-Coat RR primer to hold the surface preparation from deteriorating due to moisture or other contaminants.	No primer is required.

TABLE III-5

HEMPEL'S MARINE PAINTS

COATING SYSTEM

PROPERTY	HEMPADUR 3555
Generic Type	Nonsolvented, two-component, epoxy.
Solids By Volume	100%
Mixing Ratio (base to catalyst)	2 : 1
Dry-Film Thickness	500 microns
Surface Preparation	Sa 2-1/2 to 3
Dry to Touch	10 - 12 h @ 20°C
Ultimate Cure	7 days @ 20°C
Recoating Time	
Minimum	8 h @ 20°C
Maximum	48 h @ 20°C

4. Devoe Marine Coatings Devran 288

Devran 288 is a high-technology epoxy designed primarily for use on icebreakers or other ships trading in ice. The product is relatively new and unproven. It is presently being tested on the Canadian Coast Guard (CCG) vessel, the Sir John A. MacDonald, as a repair coating to the Inerta 160. It also is being tested on two CCG supply and buoy vessels, the Bernier and the Tracy. However, it is too early to establish a record of performance on the Devran 288. See Table III-6 for details on the coating properties.

It should be noted that the Devran 288 differs from the other three coatings in that it can be applied by conventional single-component air or airless spray equipment. This is accomplished because of a much longer pot life. At 25°C (77°F), its pot life is 2 h, whereas the other coatings have pot lives of less than 20 min. Therefore, the Devran 288 can be mixed in a container and sprayed with conventional equipment.

One disadvantage of the Devran 288 epoxy is that it must be applied in two coats. It can not be applied as thick in one wet coat as the other three coatings. The Devran 288 polymerization reaction is slower, and therefore, it would sag if applied at wet-film thicknesses of 500 microns (20 mils) or greater.

5. Other Coatings

The aforementioned high-performance coatings have gained the greatest use worldwide for service in ice. There are other similar products that are solventless, abrasion-resistant urethanes or epoxies; however, they have been marketed for other purposes.

Two products that have been used under limited ice conditions are the following:

TABLE III-6

DEVOE MARINE
COATING SYSTEM

PROPERTY	DEVROE 288
Generic Type	Nonsolvented, two-component, epoxy.
Solids By Volume	100%
Mixing Ratio (base to catalyst)	3 : 1
Dry-Film Thickness	
New Steel	2 coats @ 250 microns each
Old Steel	2 coats @ 325 microns each
Surface Preparation	Sa 2-1/2
Dry to Touch	---
Ultimate Cure	4 days @ 16°C (minimum)
Recoating Time	
Minimum	10 h @ 24°C
Maximum	43 h @ 24°C
Additional Notes	The base and catalyst are premixed in a container and sprayed by conventional single-component equipment.

- International Paints Intershield EG series;
- Mebon Paints Limited Bonslip F.

The Intershield EG series is a solvented epoxy that is applied by conventional methods in multiple coats. It has been used on ships where abrasion damage is a problem, particularly from fendering systems. It has also gained some use in underwater areas of vessels where ice has damaged a conventional coating system.

Intershield EG series is not recommended for use on icebreakers or ships travelling extensively on their own through heavy ice. It is recommended for ships trading intermittently in ice, ice-strengthened ships, or ships escorted by icebreakers. In these cases, International Paints recommends three coats at 150 microns (6 mils) per coat. Table III-7 details the properties of the Intershield.

Mebon Bonslip F is a two-component, reinforced, high-build epoxy. It was formulated to resist abrasion and corrosion, and to improve bulk material flow. It has a low coefficient of friction, which assists in the handling of bulk solids in bunkers, hoppers, chutes, etc.

It has reportedly been used on the hulls of ships travelling in ice-covered waters. However, a reference list of case histories was not available.

E. SURFACE PREPARATION

Surface preparation is undoubtedly the most important factor influencing the life of a coating system. Surface preparation determines the adhesion of the coating system to the steel substrate. Adhesion, in turn, influences the coating's ability to withstand abrasion, impact, flexure, marine fouling, and the corrosive environment of oxygenated salt water. A poorly bonded coating

TABLE III-7

OTHER COATING SYSTEMS

PROPERTY	INTERSHIELD EG SERIES	MEBON BONSHIP F
Generic Type	Solvented two-component epoxy.	Solvented two-component epoxy.
Solids By Volume	71 ± 2%	85% (spray grade) 94% (brush grade)
Mixing Ratio (base to catalyst)	4 : 1	---
Dry-Film Thickness	150 microns per coat (3 coats recommended for ice abrasion).	500 microns (spray) 200 microns (brush)
Surface Preparation	Sa 2-1/2	BS.4232* Second Quality
Dry to Touch	6 h @ 23°C	6 h @ 20°C
Ultimate Cure	3 days @ 23°C	3 days @ 20°C
Recoating Time		
Minimum	12 h @ 23°C	8 h @ 20°C
Maximum	3 days @ 23°C	48 h @ 20°C
Additional Notes	Requires Intershield EGA 780/781 epoxy primer @ 40 microns.	Requires Boncote R zinc-phosphate epoxy primer @ 25 microns.

*It is assumed that BS.4232 is equivalent to Sa 2-1/2 (near white).

would behave inadequately under conditions involving icebreaking, where all the aforementioned factors affect the coating.

Adhesion can be divided into three types:

- Chemical;
- Polar;
- Mechanical.

Chemical adhesion occurs when a chemical reaction is created between the substrate and the coating. Hot-dip galvanizing and inorganic zinc coatings are examples of this type of bond. This is the strongest bond that forms between a coating and a substrate. It has been suggested that epoxy molecules bond to a metal surface by metal hydroxide groups through a condensation reaction(37). A new chemical compound is formed when this occurs, producing a strong bond. This may explain the high adhesive strengths reported for epoxy coatings by many researchers.

Polar adhesion occurs when a resin molecule is attracted to the substrate. The polar groups are negatively and positively charged portions of the molecule that are attracted to oppositely charged areas of the substrate. This is also known as secondary valence bonding. This is not as strong as the chemical (or primary valence) bond. Most organic coatings form this type of bond.

Mechanical adhesion is associated with the roughness of the substrate (anchor pattern). Adhesion is improved if the surface is rough to enable the coating to lock into the substrate. Most of the high-performance coatings require a profile of 75 microns to 100 microns (3 mils to 4 mils).

Proper surface preparation provides maximum coating adhesion by removing contamination, scales, oxide films, and other extraneous material from the surface, as well as increasing the roughness. By increasing the actual surface area, additional reactive sites for chemical and polar bonding are created. This is important, since these types of bonds contribute most to the adhesion strength of a coating.

With this in mind the procedures, materials, and problems associated with cleaning ships in preparation for the application of a high-performance coating are as follows.

1. Procedure for High-Performance Coatings

With either new construction or an existing vessel, the first step is usually to remove any salts or other contamination with a water wash. This is achieved by a pressure wash with fresh water typically between 140 bar and 690 bar (2,000 psi and 10,000 psi). Water and brush may be used in small areas.

Any surface that is contaminated with oil or grease may not be cleaned by the water wash. In such cases, solvent, an alkali solution, or an emulsifier is used to wash down the hull.

Following the water wash, a dry-abrasive blast cleaning is used to remove shop primer, existing loose paint, rust, scale, and other contamination using silica and/or grit. The dry-blast cleaning provides the final finished surface.

Most of the high-performance coatings require at least a near-white surface preparation. A near-white surface is detailed by any of the following Standards:

- Swedish Standard Sa 2-1/2;
- Steel Structures Painting Council SP10;
- National Association of Corrosion Engineers No. 2.

Essentially, all three Standards specify that the surface shall be free of all visible oil, grease, dirt, dust, mill scale, rust, oxides, and paint, except for light shadows, stains, streaks, and discolourations. At least 95% of the surface shall be free of the discolourations.

The abrasive is usually sized to achieve a minimum profile of 75 microns (3 mils).

After the steel has been blast cleaned, it is vacuumed or blown down with compressed air starting from the top to remove grit, sand, and other contaminants.

Blast cleaning is usually performed during the first 6 hr of an 8 hr shift. There may be several blast nozzles operating at one time to provide sufficient surface area for the painters. Cleaning is more time consuming than application of the coating. The steel that is cleaned at the start of the shift is coated first, since there is the danger that it will "bloom". Normally, it is recommended that clean steel be coated within 8 hr. This is a rule of thumb because the length of time is dependent upon humidity. An area that does bloom is sweep-blast cleaned to return the steel to the original condition.

2. Equipment and Material

(a) Water-Wash Blast Cleaning

The basic water-blast equipment consists of an engine-driven pump, inlet water filter, pressure gauge, hydraulic hose, and a gun and nozzle combination. Photograph III-1 shows the unit that was used to clean an icebreaker. It is capable of a pressure of 1,380 bar (20,000 psi).

The water gun should be a "fail-safe" dump gun to relieve the pressure in case the operator releases the gun.

Various nozzles can be used which produce either a concentrated round spray or a flat fan spray.

PHOTOGRAPH III-1 - WATER-BLAST UNIT

To improve the cleaning action, sand can be injected at the blast gun before the nozzle. Usually a pressurized abrasive blast pot is used to inject the sand into the nozzle.

The cleaning rate of a water-blast unit is dependent upon the surface, the pressure, and the flow rate. If salt, oil or grease is being removed from a hull where 10% of the coating has failed and the steel rusted, the hull could be cleaned at a rate of 42 sq m/h to 67 sq m/h (450 sq ft/h to 725 sq ft/h) per gun(38). This would be achieved at a pressure approaching 690 bar (10,000 bar) and a flow rate of 45 L/min (10 ga/min)(39). At lower pressure and flow rates (140 bar and 23 L/min), the cleaning rate would be reduced to 14 sq m/h (150 sq ft/h) per gun.

To assist in the removal of oil and grease, the following chemical cleaners can be used:

- Petroleum solvents such as kerosene, mineral spirits, or naphtha;

- Chlorinated solvents such as trichlorethylene or 1, 1, 1-trichloroethene;

- Alkaline cleaners composed of sodium-hydroxide silicates and carbonates and surfactants, sequestering agents, inhibitors, wetting agents, and/or soaps;

- Acid cleaners with small quantities of surfactants, water-miscible solvents, and organic wetting and emulsifying agents;

- Detergents consisting of buffering salts, sequestering agents, dispersants, inhibitors, wetting agents, and/or soaps.

Solvents are generally not used because of health and safety regulations, except for small area cleaning. For larger areas, water-based acidic or alkaline cleaners are used. The acid cleaners are normally used cold, while the alkaline cleaners are used at elevated temperatures.

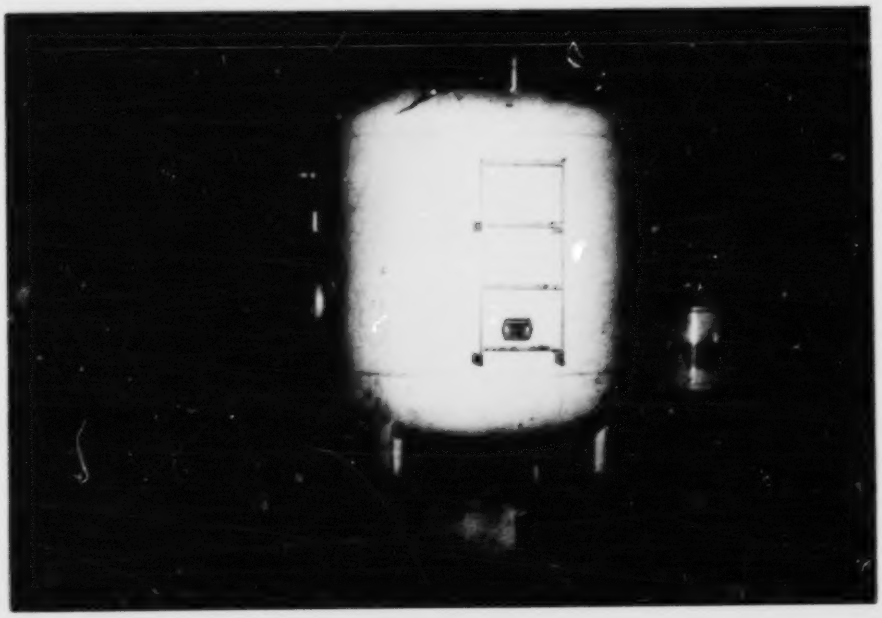
The chemical cleaners can either be injected into the hot stream of water before the nozzle or premixed in a reservoir and pumped directly through the nozzle.

(b) Abrasive-Blast Cleaning

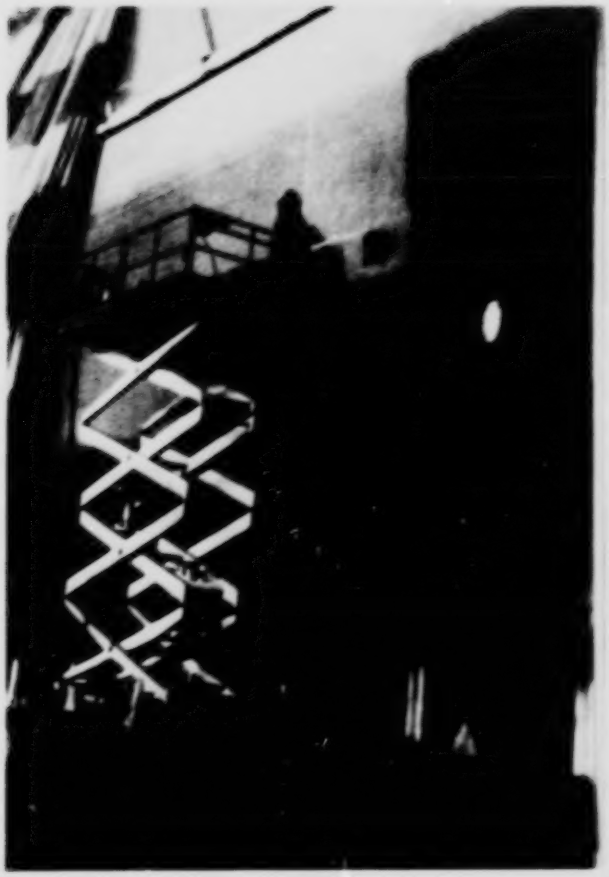
The abrasive-blast equipment consists of an air supply, air hose, couplings, abrasive-blast machine, abrasive-blast hose, nozzles, operator equipment, air-fed hood, and control valves, and oil and moisture separators. Photographs III-2 and 3 show a pressurized blast machine and an operator blast cleaning the hull of an icebreaker.

Two types of abrasive-blast equipment are used in cleaning most ships. The pressure-type system is under a pressure of 6 bar to 7 bar (90 psi to 100 psi) and is the most productive method of blast cleaning. It delivers the abrasive at a higher velocity than the suction-blast method. The suction method is not under pressure. Abrasive is merely sucked from the container. The pressure-type method cleans the steel 33% faster than the suction method.

The commonly used abrasive materials consist of silica sand and slags (either copper or nickel). Silica



PHOTOGRAPH III-2 - PRESSURIZED BLAST MACHINE



PHOTOGRAPH III-3 - OPERATOR BLAST CLEANING ICEBREAKER HULL sand is white in colour, has a high degree of dusting, is round in shape, and can not be reused. In comparison, the commonly used copper slag is harder, angular in shape, black in colour, with a low degree of dusting, and good reusability. Depending upon the particle size of the abrasive, the average maximum profile height is about 75 microns (3 mils) for either product (medium particle grade).

The copper slag now appears to be more commonly used than silica abrasive. Presumably, this is because of health regulations concerning silicosis.

The cleaning rate is dependent upon the surface condition, nozzle size and pressure, and abrasive type and size. A steel surface with adherent rust scale and significant pitting will require more time and abrasive than a surface with a loose scale and no pitting. Increasing the nozzle pressure to 7 bar (100 psi) from 4 bar (60 psi) will double the production rate. A 9.5-mm (3/8-in) nozzle will clean an area 2-1/2 times the size of the area cleaned by a 6.3-mm (1/4-in) nozzle in a similar period of time.

Using a 9.5-mm (3/8-in) nozzle and a pressure of 7 bar (100 psi), 16/40 silica sand has a cleaning rate of 26 sq m/h (285 sq ft/h)(40). Under similar conditions, a copper slag has a production rate slightly lower at 24 sq m/h (262 sq ft/h). These rates produced a near-white finish on newly fabricated steel.

Marine Industries Limited in Sorel, Quebec, report typical production rates of 9 sq m/h (100 sq ft/h) to achieve a near-white finish on new vessels using a silica sand. The nozzle size and pressure were not specified. It is assumed that a smaller nozzle or lower pressure was used.

During the fabrication of a new vessel, the steel plate may be blast cleaned in the shop by centrifugal blast cleaning (or better known by the trade name, Wheelabrator) using steel shot or steel grit. This method is well adapted for cleaning large numbers of small parts. Both abrasives achieve a very clean surface, however, the profile differs. The steel shot peens the steel and does not give a good surface profile. Often, steel grit is added to the shot to improve the anchor profile. Compared to air-blast cleaning, the automated process can save time, labour, energy, and abrasive consumption.

After cleaning, the steel plate would receive a shop primer to prevent deterioration of the blast cleaned surface. Several Canadian icebreakers received a coat of vinyl primer during construction to hold the hull surface preparation until it was ready for the Inerta 160.

Depending upon the preference of the owner and the shipyard doing the work, the steel plate may be coated in the shop using the high-performance coating, with the exception of the weld areas. Consequently, only the weld areas would require blast cleaning and coating in the dry dock. In Finland, Oy Wartsila Ab uses a cutback of 500 mm (20 in) at the welds.

In Finland, it is commonplace to construct a vessel in large sections in the shop, rather than in a dry dock, as is done in Canada. Steel plate is Wheelabrated in the shop and primed. The plates are then welded together, forming a section of the hull. The primer is then removed by air-blast cleaning in the paint shop, and the hull is coated with Inerta 160. The building environment is controlled for ideal blast-cleaning and coating conditions. The buildings are heated, and the air is circulated and vented outdoors to control dust and fumes. The spent abrasive material (steel grit) is removed by front-end loaders and dumped into a floor grating, where it is carried by suction through rubber piping for storage in silos. The used abrasive is then mixed with the new material and is reused.

(c) Grinding of Welds

The grinding of welds on icebreakers is not common. The quality of the welds is usually very good. If grinding is required, it is done to remove only sharp protruberances prior to application of the high-performance coating. This is most likely to occur where manual stick welding is used, particularly with overhead welds.

3. Problems Involving Surface Preparation

The problems associated with surface preparation appear to be common to all steel structures requiring a superior surface finish. There is no problem unique to the cleaning of icebreaker hulls. The most important factor that must be kept in mind at all times is that the severe conditions of operating in ice-covered waters requires excellent surface preparation for maximum coating adhesion.

One problem noted by Canadian shipyards is the difficulty encountered in blast cleaning a very rough, corroded hull where the pits are not rounded, but instead, are grooves that undercut the steel. The abrasive particles do not penetrate these grooves, and it is difficult to remove all rust and contamination.

Sand or mixed grits are reported to clean corrosion pits better than steel shot or grit because the particles explode upon impact and scour the sides of the pit. Water blasting at high pressure will also help.

Operator problems that were encountered included the frequent replacement of visors on the helmets from the dust problem associated with blasting in a restricted area. Two Eastern Canadian shipyards report the frequent replacement of the glass visors caused by abrasive particles marking the glass. In restricted areas, the visors are replaced several times a week. In unrestricted areas, the visors may be replaced weekly. Canadian Shipbuilding & Engineering Ltd. in Collingwood, Ontario, uses a replaceable plastic film on their visors to reduce the cost. The plastic film may be replaced once or twice per shift.

Another area of potential problems is the critical task of inspection. Inspection of the blasted surface should be conducted on a full-time basis by a qualified third party. Most owners leave the inspection to the coating supplier. This can cause problems, since the inspector is required to pass judgement on the quality of the shipyard's or coating contractor's work. A decision unfavourable to the shipyard could affect in future sales to the shipyard. Therefore, there is pressure on the inspector to side with the shipyard. To avoid a conflict of interest, the ship owner should designate an independent third party for the inspection. A Finnish shipping company, Oy Henry Nielsen Ab, confirmed that they have experienced this problem.

It should also be noted that the high-solids materials that are applied as a hot mix should not go on a cold substrate. Poor wetting can result, causing poor adhesion, particularly if applied as a very thick film.

F. COATING APPLICATION

The application of the high-performance coating to the icebreaker is as important as the surface preparation. All the icebreaker coatings are applied by heated, two-component spray, except for the Devran 288, which is premixed and sprayed by conventional, single-component equipment. Despite the fact that plural-component coatings have been used in shipyards since the late 1960s, there are still yards where painters are not familiar with or well trained in the application of 100%-solid coatings. This can lead to problems when using coatings such as Inerta 160, Hempadur 3555, and Zebron.

The procedures and equipment used in coating icebreakers, and the problems associated with the work, are as follows.

1. Procedure for Coating Icebreakers

(a) New Construction

Currently, most shipyards blast clean the steel plate in the shop by centrifugal blast cleaning. The plate is then coated in the shop with primer or the high-performance coating.

The hull is then constructed in the shop or in the dry dock. If it is constructed in the dry dock, the primer is removed upon completion of the hull, and the high-performance coating is applied. If it is constructed by sections in the shop, the section is moved by flat-bed truck to the paint shop, where the primer is removed and the high-performance coating is applied. The primary difference between the various procedures is the location of the high-performance coating application. When it is applied in the shop, the environmental conditions can be controlled more easily.

None of the coatings require a primer, except for Zebron 386-4.

The coating materials are usually kept at a temperature of 20°C to 25°C (68°F to 77°F) prior to being used. The material is then transferred into containers where it is heated. For example, the Inerta 160 is circulated for 15 min to 30 min until the material is at a temperature of 60°C to 70°C (140°F to 158°F). The heater is located between the pump and the gun, and circulation takes place throughout the entire set of hoses. Once the proper temperature is reached, the circulation is switched off, and the pressure in the main pump is increased to 200 bar to 300 bar (2,900 psi to 4,350 psi).

The proper nozzle-tip size is selected, and the ratio of the dosage pump is set at 2 : 1, with the Inerta 160 or the Hempadur 3555. The Zebron mix ratio is 3 : 1.

When spraying is ready, the mixing gun is turned to the spraying position, and the material is applied, ensuring that the proper spray pattern is attained. For high-viscosity coatings, the distance of the gun from the surface should be 350 mm to 400 mm (14 in to 16 in). The spray-pattern width should be 250 mm to 400 mm (10 in to 16 in)(41).

When the work is interrupted or terminated, the equipment must be flushed out with solvent. It is particularly important that the mixing tube, hose, and pistol be cleaned. Teknos-Maalit Oy of Finland recommends a 15-min wash time for the Inerta 160.

All the coatings are applied in a single coat using the multipass technique to build the thickness to 500 microns to 1,000 microns (20 mils to 40 mils). This is done primarily to eliminate intercoat delamination. The Zebron is particularly effective in this regard. It is reported that it can be built up to 12.7 cm (5 in) thick. Only the Devran 288 is applied in two coats.

Welds and other rough areas should be stripe coated just prior to the application of the primary coat. This will minimize and prevent pinholing, which has been noted on several Canadian icebreakers using Inerta 160.

The manufacturers' technical data and application instructions for each product are attached as Appendix II.

(b) Existing Vessels

Existing vessels may require a filler coat prior to the application of the primary coat, depending upon the extent of the pitting corrosion.

International Paints markets Inerta 160 stopper as a filler for severely pitted steel. Essentially, it is the same material as Inerta 160, with inert fillers added to increase the bulk. It is applied by spray and then smoothed into the pits using a broad putty knife with a width of 20 cm to 30 cm (8 in to 12 in).

Hempel Marine Paints also offers a filler material with their coating system. Hempadur Filler 3564 is used to fill pitted areas of the hull.

Reliance Universal and Devoe Marine do not offer any filler materials with their product line. Instead, the Zebron and Devran 288 coatings can be spray applied and squeegeed into pitted areas. Devoe Marine does recommend a thicker coating for old steel (325 microns) than for for new steel (250 microns). The Zebron products can be applied very thick by spray application using the multipass technique. This would compensate for a very rough hull.

On many icebreakers the coating application involves the repair of an existing system. Often, sections of the coating have not been damaged by the ice and are still adherent. To reduce costs, it is common practice to leave the existing coating on the hull, roughen it, and apply the new coating over it. This involves attempting to feather the edges of the old coating to provide a smooth transition from the old to the new. Feathering the edge reduces the chance of the ice catching on the boundary between the two coats. It also roughens the old coat, thereby, improving the adhesion between the two.

Antifouling paints have been used in conjunction with Inerta 160 in Finland on passenger ferries. The antifouling used was International Interspeed Premium Bla600 or Bla610 (copper-based, chlorinated rubber applied 50 microns [2 mils] thick). It was applied 6 h after application of the Inerta 160 at an ambient temperature of 20°C (68°F). The antifouling paint was applied to the entire bottom, except for a 2-m to 3-m wide band at the ice line.

2. Equipment

All the coatings are applied by two-component, heated airless spray, except Devran 288. Inerta 160, Hempadur 3555, and Zebron all recommend the use of Graco Hydra-Cat plural-component equipment.

Airless spray equipment relies on hydraulic pressure to produce the desired spray. Most of the units used are driven by air; however, they can also be electric or gas powered.

The high-viscosity high-solids coatings are delivered at high pressures, typically 160 bar to 300 bar (2,320 psi to 4,350 psi). The hydraulic pressure is usually controlled by the pressure in an air cylinder. This, in turn, influences the fan pattern of the spray. Insufficient pressure can cause streaks or fingers in the fan pattern. Increasing the pressure to the proper level evens out the spray to produce a smooth fan.

The two-component airless spray gun is a simple device that merely mixes the two components and directs the spray in the proper direction. The size and shape of the orifice tip determines the amount of material flowing and the size and shape of the fan. The epoxies (Hempadur 3555 and Inerta 160) require a tip size of 0.53 mm to 0.68 mm (0.021 in to 0.027 in). The range in tip sizes for the Zebron is larger at 0.48 mm to 0.94 mm (0.019 in to 0.037 in).

The liquid coating is heated by an in-line heater which heats the liquid as it passes through the spray gun. The material is heated to reduce viscosity.

Devran 288 is applied in the same manner, except that it is premixed, and single-component airless equipment is used.

3. Problems with Coating Application

When two-component high-solids heated coatings are applied, many problems can arise, including the following:

- Improper mix ratio of base to catalyst, resulting in improperly cured patches of coating. This has been observed for both Zebron and Inerta 160;

- Low coating-material temperature or pressure, resulting in a poor spray fan. The material "fingers", resulting in a nonuniform surface finish on the coating;

- The short pot life can cause the material to polymerize inside the spray equipment if it is not properly cleaned with solvent;

- Wet films that are excessively thick will sag;

- Dry films that are excessively thick may cause the coating to pull away from the steel, crack, or check as it cures;

- The fast cure and insolubility of the cured film presents problems for recoating. A second coat should be applied within the recommended recoat time, otherwise intercoat delamination will result;

- Multiple-coat systems should be avoided. Intercoat delamination occurs in spite of roughening the previous coat by abrasive blasting. This has been seen on Canadian Arctic icebreakers with the Inerta 160 system, where a second coat was applied after keel blocks were repositioned;

- Feathering or removal of an existing coating is time consuming and expensive because of the superior abrasion resistance of the coatings;

- Porosity can occur at welds or other rough areas, unless the area is stripe coated or filled with the coating or a filler material;

- Improper tip size and shape can result in a poor spray fan, plugging, or an excessive material flow rate;

- Improper gun-to-hull distance can result in a rough, nonuniform coating.

G. CONTROLLED ENVIRONMENTS

The conditions under which a coating is applied are very important to the life expectancy of the coating. Coating application to existing ships' hulls is always done in a dry dock. New construction can be coated both in the shop and in a dry dock. The minimum requirements for applying a high-performance coating generally are the following:

- A relative humidity less than 80%*;
- An ambient temperature greater than 5°C (41°F);
- A steel temperature at least 3°C (5.4°F) above the dew-point temperature;

It should be stressed that these are the minimum requirements. Ideally, a temperature of at least 15°C (59°F) for the air and steel is desirable. These conditions are usually attainable in the shop; however, in the dry dock it may be impossible, unless a shelter is constructed. Dry docks are generally cool and damp, since they are adjacent to a large body of water. Cleaning and coating an icebreaker usually takes one to two weeks, during which, the weather could be windy, cool, and wet. At night, fogs can roll in from the ocean or lake. Therefore, it can be seen that shelters are a necessity. Without them, all parties concerned are risking production of an inferior coating system. The owner should specify that shelters be used.

Present technology uses the following types of controlled environments.

1. Coating Shop

Most shipyards have some type of shop in which the steel is blast cleaned and coated. The shop equipment usually consists of centrifugal blast-cleaning equipment and conventional air and airless spray units. Many of the yards do not own the specialized equipment needed to apply the plural-component, high-solids coatings. The equipment is usually rented for specific projects. The steel plate and small pieces are coated in these shops for assembly into larger sections in the dry dock.

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*See Appendix IV

As previously discussed, the shipyards in Finland (primarily the Oy Wartsila Ab yards) use small shops to prime the plate for construction elsewhere. The assembled larger section is then moved indoors to a large paint shop on a flatbed truck. The primer is then removed by blast cleaning, and the entire section is coated, except for weld cutbacks, with the high-performance coating (usually Inerta 160). It is allowed to cure in a controlled environment and then is transferred to the dry dock.

In either instance, the shelter is the shop itself. The shop is vented and the temperature is controlled. Oy Wartsila Ab has specifically constructed their shops to overcome the problems of coating in a dry dock. Only weld and repair areas are coated in the dry dock.

The Finnish paint shops are approximately 45 m by 28 m by 17 m in height (150 ft by 90 ft by 55 ft). The building is constructed of steel, is insulated, and has a folding door at one end.

The ventilation system circulates the air from the roof to the floor with the outlet vents in the lower walls. This scheme reduces the dust from blast cleaning and the fumes from painting. Any coating process in an enclosed space offers a risk of explosion from solvents used in the process. Any such coating operation should involve regular testing for hydrocarbons in the ambient space. The use of solventless coatings, of course, reduces the hazard of fire and explosion.

Portable oil heaters are used to heat the shelter during the winter months.

No method is used to control the relative humidity. The Finnish winters are normally dry and cold, and the relative humidity is usually 30% to 40%. It can be higher in the summer; in which case, they do not paint if conditions are not correct.

The paint materials for these shops are purchased and stored in reusable 800-L (176-ga) drums. The containers are returned to the paint manufacturer where they are cleaned and reused. The paint is pumped to the painting area by Graco pumps using a permanently installed piping system.

The blast material is steel grit which is collected and reused as detailed in the previous section on surface preparation.

2. Dry Dock

In Finland, Canada, and the United States, dry-dock shelters are constructed only when absolutely necessary. Shelters are constructed when the weather is cold and wet, otherwise they add to the expense, and most shipyards do not like to use them.

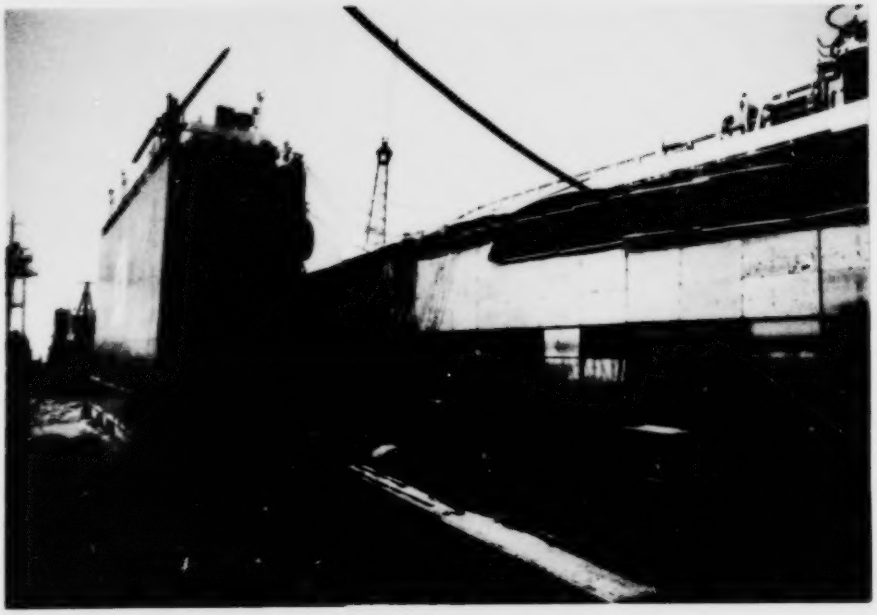
Typical dry-dock enclosures are shown in Photographs III-4, 5, 6, and 7. The first two show an enclosure that consists of nothing more than tarpaulins and scaffolding. Many of the Canadian shipyards use an enclosure similar to this one. If the work is done in a graving dock, the walls of the dock may be used instead of scaffolding. Plywood sheets or timbers with tarpaulins would then be run between the ship deck and the top of the graving dock.

Photographs III-6 and 7 show a shelter constructed from plywood sheeting, angle iron, and tarpaulins in the Canadian Arctic. The walls consist of plywood sheets and an angle-iron frame. Each section consists of several plywood sheets. The sections are then welded together to form a wall. The walls

PHOTOGRAPH III-4 - CANMAR KIGORIAK DRY DOCKED AT McKINLEY BAY, N.W.T.

PHOTOGRAPH III-5 - TARP ENCLOSURE AROUND KIGORIAK

PHOTOGRAPH III-6 - PLYWOOD SHELTER AT DOME DRY DOCK AT McKINLEY BAY



PHOTOGRAPH III-7 - PLYWOOD SHELTER (same as III-6)

PHOTOGRAPH III-8 - COMPLETED ENCLOSURE AT THE STERN OF THE VESSEL

are, in turn, supported by angle-iron bracing to the dry dock and to the ship. Tarpaulins form the roof of the enclosure extending from the wall to the deck of the ship. Photograph III-8 shows the completed enclosure at the stern of the vessel.

The shelter noted in Photographs III-6 and 7 was heated by portable heaters fueled with propane or diesel. Two large heaters provided 4.3 million Btu/h. Seven smaller portable heaters each provided an additional 315,000 Btu/h (see Photograph III-9).

The temperature within the shelter prior to heating was -40°C (-40°F). Once heating began at 10 million Btu/h (2,930 kW), it took approximately 24 h to raise the steel temperature at the stern to 0°C (32°F). The air temperature at that time was approximately 27°C (81°F). The relative humidity was 15%, and the dew-point temperature was -2°C (29°F). It took at least another 24 h to raise the temperature of the stern hull to 10°C to 15°C (50°F to 59°F).

Relative humidity was not a problem, and so, no control was required.

Four to five days of round-the-clock work were required to construct the shelter. It is probably one of the more expensive shelters constucted, but it does have advantages. It will retain the heat better than a tarpaulin shelter, and there is greater space to maneuver equipment and manpower.

Within the various shelters, scaffolding and hydraulic lift equipment are used by the contractors to assist in blast cleaning and coating the hull. Photograph III-5 shows a hydraulic lift used to gain access for blast cleaning the hull.

In Finland, Oy Wartsila Ab used scaffolding that conformed to the shape of the hull. The scaffolding was welded to the side of the ship at the boot top and at the bottom. It had six platforms at different elevations that the crew could work on. Once the work was completed in that area, the platform was cut free of the hull, moved by an overhead crane to the next area, and rewelded to the hull.

Marine Industries Limited in Sorel, Quebec, also uses scaffolding to construct shelters for ships. However, to expedite the installation of the tarpaulins, the canvas is stored on large rolls. These are lifted to the top of the scaffolding and unrolled. The joints are then taped to make the enclosure weather tight. To vent their shelter, Venturi suction fans are used. Electric fans are not used because of the danger of an explosion from the paint fumes. Heating is provided by two, one-million Btu/h heaters. One is installed at each end of the ship.

Most of the high-performance coatings require 4 to 7 days to cure adequately. This means that the temperature within the shelter must be maintained at 15°C to 25°C (59°F to 77°F). Usually, ship owners are not willing to tie up their vessel any longer than necessary, and the ships commonly enter the water prior to the coating completely curing. Most of the high-performance coatings will continue to cure underwater, but such curing is temperature-dependent. If the work is done on the west coast of Canada in July, the water temperature could be 15°C (59°F), and there would not be a problem. However, if the work is done in the Canadian Arctic in November, the ship should not enter the water until all areas of the hull have completely cured. Even during the summer, the water temperature in the Beaufort Sea may not exceed 5°C (41°F).

Fire and explosion within shelters become a danger when solvent-bearing coatings are used. In shelters with forced air heating (direct or indirect-fired heaters) the solvent should be swept away as heated air is forced into the shelter. Air expelled from the shelter should not be recycled. If electrical heating is used in the shelter a definite hazard exists if air is not continually removed. In the absence of

PHOTOGRAPH III-9 - PORTABLE HEATER

flushing action solvent levels may build up and the solvent-air mixture be ignited by the hot electric heating elements or any spark source. While heat conservation is desirable, it should not be achieved at the expense of safety.

While use of solventless coatings eliminates the major source of flammable volatile solvent in a coating operation, it is not safe to assume a flammable vapor will not be produced. Applicators use solvents for cleanup and sometimes, when the coating application is difficult, will add solvent to the paint even though instructed to the contrary.

H. COSTS/PRODUCTION RATES

1. Shelter Construction

(a) Canada

Undoubtedly, the most expensive shelter to construct and heat would be one in the Canadian Arctic. The cost of construction includes the transportation of the materials to the site. The materials must either be flown or barged into the area. In addition, the shelter must be weatherproof and insulated to retain the considerable heat input required to heat the steel from outdoor temperatures which commonly are at -40°C (-40°F).

A crew of 10 to 15 was required for 4 to 5 days to hoard in a large Canadian icebreaker. Construction continued around the clock. Therefore, the total work time probably exceeded 100 man-days. The equipment included welding units, two hydraulic truck cranes, and two hydraulic bucket trucks.

Shipyards in Eastern Canada report similar construction expenditures in labour. Davie Shipbuilding Limited reports that several thousand man-hours are required to construct shelters consisting of timber and plastic sheeting. Port Weller Dry Docks reports similar time expenditures on work for the Canadian Coast Guard icebreaker, Des Groseilliers.

The labour expended to hoard a ship is dependent upon the size of the vessel, the type of shelter, and the experience of the shipyard. Marine Industries Limited reports that a shelter for a 90-m long vessel can be constructed in approximately 500 man-hours. On the Camille Marcoux passenger ferry, a scaffold-and-canvas shelter was constructed. Port Weller Dry Docks believes that a realistic figure for time expenditure would be 1,000 man-hours.

Most of the Canadian shipyards do not keep separate costs for heating the shelters. The shipyards state that the costs can vary, depending upon the time of year in which the work is done.

Most of the shelters are easily stored, since they usually consist of plywood sheeting or scaffolding that can be disassembled and stacked. The tarpaulins are either folded or rolled. Storage costs are negligible.

(b) Finland

In Finland, dry-dock shelters are constructed in a manner similar to those in Canada. Scaffolding, tarpaulins, and plastic sheeting are used. However, shelters are not normally used on the icebreakers because dry docking takes place during the warm summer months. Time expended to construct the shelters is similar to Canada.

To heat the large shop shelters used at the Oy Wartsila Ab yards in 1983, 1.5 million L (330,400 ga) of oil was used. Most of this was used during the winter months. Winter in Finland is similar to the winters experienced in southern Canada.

2. Abrasive Blast Cleaning

The costs for abrasive blast cleaning an icebreaker are dependent upon the age of the vessel. With new construction, the costs are lower since the steel is new and relatively smooth, and the only existing coating may be a primer. The costs can be considerably higher if the steel is severely pitted from corrosion (the pits must be filled with coating material) and patches of a previous abrasion-resistant coating are present.

On new construction, the task is simplified by centrifugal blast cleaning the plate and coating it immediately with either primer or the high-performance coating. Cleaning costs in the dry dock are greatly reduced when this procedure is used.

Marine Industries Limited reports cleaning rates for each gun of 9 sq m/h (100 sq ft/h) using a silica sand on new ships. A crew may consist of 16 to 20 men working an 8-h shift. Two men would alternate hourly on each gun. While one man is blast cleaning, the other would handle the equipment and make sure the blast pot is charged with abrasive material. At this rate, a new icebreaker with a hull surface area of 25,000 sq ft could be blast cleaned in three days. The rate of cleaning would be approximately 4.5 sq m/man-hour (50 sq ft/man-hour).

To feather existing Inerta 160 by abrasive blasting, Marine Industries Limited estimates that 1 sq ft (0.3 sq m) can be feathered per hour. This is because of the very good abrasion-resistant properties of the material. Teknos-Maalit Oy of Finland estimates that 100 kg of sand is required to remove 1 sq m of Inerta 160; whereas, 20 kg of sand is required to clean bare steel to a near-white finish.

Marystown Shipyard Ltd. in Newfoundland reports similar cleaning rates on the Canadian Coast Guard vessel, Tupper. This ship had a conventional hull paint system.

Exact costs for cleaning alone were not available from the shipyards or the owners. The cleaning costs are usually combined with coating application in an overall contract price.

3. Cleaning and Coating Application

(a) Canada

Most of the vessels that have received the abrasion-resistant coatings are existing vessels that have been in service for anywhere from two or three years to in excess of 30 years, although in recent years, many new vessels have also received the coatings. The costs generally are lower for those vessels with hulls in good condition (very little corrosion), with no abrasion-resistant coating to be removed, and ones that are dry docked in southern Canada. The higher costs are associated with Arctic dry docking, for corroded hulls, and where an existing high-performance coating must be feathered or removed.

Table III-8 lists the costs of dry docking, cleaning, and coating the various Canadian Coast Guard vessels in eastern Canada. The costs vary from \$65 to \$161/sq m (\$6 to \$15/sq ft) during the years 1978 to 1982. Most were new coating applications (not repairs to existing coatings), except for the Montcalm and the Tupper.

It is difficult to compare the individual vessel coating costs because different shipyards did the work, the ships are different sizes, the hulls were corroded to varying degrees, and some of the work was performed using shelters.

TABLE III-8

COSTS OF DRY DOCKING, CLEANING, AND COATING

VARIOUS CANADIAN COAST GUARD VESSELS IN EASTERN CANADA

VESSEL	APPROXIMATE YEAR OF CONSTRUCTION	YEAR OF COATING	COATING APPLIED	SURFACE AREA (m^2)	COST ($)	REMARKS
Louis S. St. Laurent	1970	1977	lnerta 160	1,860	120,000	All of hull, except midship, bottom, and portion of stern.
Pierre Radisson	1978	1982	lnerta 160	2,780	250,000	New coating.
Labrador	1953	1979	lnerta 160	2,360	*50,000	New coating.
Montcalm	1957	1979 1981	lnerta 160 lnerta 160	1,200 140	90,000 35,000	New coating. Coating repair.
Tupper	1959	1982	lnerta 160	465	50,000	Bow/water-line coating repaired.
Montmagny	1963	1981	lnerta 160	420	65,000	New coating.
Beauport	1960	1979	lnerta 160	700	55,000	New coating.
Ville Marie	--	1980	lnerta 160	390	63,000	New coating.

*This cost does not include cleaning or coating application to the hull.

The coating on the Montcalm was repaired in 1981 at a cost of $35,000 for 140 sq m ($1,500 sq ft). This cost is very high. It demonstrates the difficulty of removing or feathering the Inerta 160.

The aforementioned costs were obtained from the Laurentian Region of Transport Canada and the Maritimes Region of the Canadian Coast Guard. Costs for other work performed by the shipyards were not made available.

More recent costs for work on Arctic Class 3 icebreakers are in excess of $600/sq m ($60/sq ft). This is an all-inclusive cost based on dry docking in Vancouver. It includes dry-docking charges, material, equipment, shelter, and labour. Labour accounts for approximately one half the total. The cost is undoubtedly high because, on this particular vessel, the work consisted of recoating only 700 sq m (7,500 sq ft) of damaged coating. Had the surface area been larger, the costs of the shelters, heating, dry dock, etc., would have been distributed over a larger area, and the cost per unit area would have been reduced.

Costs for cleaning and coating work in the Arctic are considerably higher and can be more than double the cost of similar work in southern Canada. Recent costs for work done in the Arctic have been approximately $1 million. On one icebreaker that had approximately 1,700 sq m (18,000 sq ft) of coating repair, the cost was about $620/sq m ($58/sq ft). For additional work on the ship, the cost would have been only $250/sq m ($23/sq ft).

One of the major costs of Arctic work involves transportation of materials, equipment, and personnel to the site. This represents approximately 10% of the total cost. Accommodation accounts for another 10% of the total. Construction of the shelter and heating represents an additional 5% to 10%. Therefore, before any blast cleaning or painting work has even been performed, $250,000 to $300,000 has likely been expended.

(b) Finland

The Finnish Board of Navigation has Inerta 160 on all their icegoing vessels. The most recent icebreaker constructed, Sisu, cost 480,000 Finnish Marks (mks) to coat in 1982. The surface area coated consisted of 3,500 sq m (37,700 sq ft). In 1984 terms, the unit coating cost is approximately $31/sq m ($3/sq ft). It is expected that the new icebreaker, Karhu II, (to be completed in 1986) will cost approximately 600,000 mks to coat. It should be noted that these are new-construction costs, not recoat costs.

The icebreaker typical size is as follows:

- Length: 69 m to 95 m;

- Breadth: 17 m to 24 m;

- Depth: 6.8 m to 8.3 m.

The cost per area is usually lower for the larger vessels.

The average cost to clean the hull and apply Inerta 160 to a vessel is 150 mks to 250 mks/sq m ($34 to $57/sq ft). This is one third to one half the cost of performing the same work in Canada. Salary differences account for most of the difference. Painters and sandblasters in Finland are paid an average of 40 mks/h ($9/h). In Canada, the salaries are two to three times higher.

The shipping company, Oy Henry Neilsen Ab, has had five vessels coated with Inerta 160. To coat the Tebo Star, the 1984 cost was 650,000 mks ($148,000 Canadian). The unit cost for the vessel was approximately $33/sq m ($3/sq ft).

I. DISCUSSION OF COATING CASE HISTORIES

The information in this section was obtained from the following sources:

- Trip to eastern Canada in 1983;
- Correspondence with the United States Coast Guard in 1983;
- Trip to Finland in 1984;
- Information from Canadian Marine Drilling Ltd. in 1984 and 1985.

1. Canada

(a) Davie Shipyard - Levis, Quebec

Their experience with low-friction coatings lies with the Inerta 160 which they have applied to three structures, two ships and one steel caisson. One of the ships was the Newfoundland ferry, the Robert Bond.

In each case, the coating was applied in May or June. Most of the application work was done in the shop. They blast clean a section, mask the edges to be welded with tape, and then spray on the Inerta 160. They apply Inerta 160 outdoors only in the weld areas. Since their work was done in the early summer, they could select favourable weather, and shelters were not used.

In the case of the Robert Bond, the ship was an existing ferry from which they removed the old coating (conventional paint system) by blast cleaning the surface with steel grit. The Inerta 160 was then applied. No shelters were used.

None of these ships have returned to the shipyard for repair work up to March of 1983; therefore, they have no information on the performance of the Inerta 160.

Prior to application of the Inerta 160 to weld areas they grind the manual stick welds smooth, but not flush to the surface. The manual welds tend to be roughest.

They generally avoid painting ships outdoors during the winter months because of the cold temperature and the wind problem. They also have problems with ice and snow removal from the dry docks in the winter.

The shelters they have built consisted of plastic sheeting on top of timbers laid between the top of the ship and the top of the dry dock. They also have constructed shelters using plywood sheeting leaned against the side of a ship.

They have no experience with applying antifoulants to Inerta 160.

(b) Collingwood Shipyards - Collingwood, Ontario

Collingwood Shipyards has had experience on one ship only; the tug, Pointe Sept Isles, owned by the Eastern Canada Towing Company. The tug was constructed in 1980 and coated in late February and early March.

The hull sections were grit cleaned in the shop by Wheelabrator and coated with Inerta 160 to a thickness of 750 microns (30 mils). The weld areas were primed only in the shop. The welds were then reblasted in the dry dock and coated with Inerta 160. The blasting roughened the existing Inerta 160 to provide good adhesion between the Inerta 160 applied to the weld areas in the dry dock and that applied in the shop.

The manpower required to clean the hull was 400 man-hours. The ship is 32 m by 10.6 m by 6 m (deep) (105 ft by 35 ft by 20 ft).

The coating application in the dry dock was done under a shelter constructed of 2 x 4 wood, scaffolding and tarpaulins. At the top of the shelter, boards were laid between the scaffolding and the ship. The tarpaulins were tied to the scaffolding and laced to each other. It is estimated that it took three to four days to construct the shelter.

The surface temperature of the ship in the heated shelter was about 18°C (64°F). The ambient temperature outside the shelter was about 5°C (41°F) during the day and -5°C (23°F) at night. Heat was blown into the shelter by four gas-fired heaters. The relative humidity in the shelter ws not measured because typically it is low during the winter months.

There was some problem in coating the weld areas because they were not ground smooth.

Not all areas of the ship could be coated in the dry dock due to the placement of the keel blocks. This was overcome later when the tug was floated into the water for further outfitting. When it was moved back into the dry dock, the areas where rust was bleeding through the coating at pinholes and the previously inaccessible areas were recoated.

The tug was inspected in April 1981, and the coating was in good condition.

(c) Port Weller Dry Docks - St. Catherines, Ontario

Two ships have been constructed and coated with a low-friction hull coating by Port Weller Dry Docks. The Canadian Pioneer, a bulk carrier owned by Upper Lakes Shipping Ltd., was coated in the bow area only in September 1981. The Des Groseilliers, an Arctic Class 3 Icebreaker owned by the Canadian Coast Guard, had its entire hull coated in September 1982.

Both ships were blast cleaned to a near-white condition in the dry dock. Both were coated with a shop primer to prevent corrosion prior to coating. The primer was then blasted off, and the Zebron polyurethane was applied to each vessel. The Zebron coating was applied 1,000 microns (40 mils) thick in one application to the Des Groseilliers. There was no primer or antifoulant applied.

A shelter was constructed for the coating application on the Des Groseilliers. It consisted of polyethylene sheeting and wooden scaffolding around the bow end and planking and polyethylene sheeting between the ship and the dry dock on top.

Two heaters were used to heat the shelter. Air was blown over steam coils to avoid the obvious problem of moisture condensation from combustion gases. There was no method used to control the relative humidity. To vent the shelters fans were placed on the top of the ship.

The construction of the shelter consumed 2,500 man-hours. Port Weller Dry Docks admit that they were inefficient and the work could have been done in 1,000 man-hours if they had been well organized.

Welds were ground flush on the bow area of the Des Groseilliers. Peaks were ground smooth on other welds on the hull. The welds were then blast cleaned to give the steel a profile for improved coating adhesion.

No shelter was used during the work on the Canadian Pioneer.

The Canadian Pioneer's Zebron coating failed in the bow area after only six months. The cause of the failure may have been mismetering of the two-component mix, a common problem noted with Zebron jobs. It was recoated in May 1982 and appears to be performing satisfactorily.

(d) Marine Industries Ltd. - Sorel, Quebec

Marine Industries Ltd. has probably had the most experience with low-friction hull coatings of all the Canadian shipyards visited.

Most of their experience has been described previously. Marine Industries Ltd. has noted several problems when applying the Inerta 160 coating. The coating tends to bridge over pits, rather than penetrating into the pits on badly corroded areas. The coating eventually flakes off in the areas since there is no adhesion to the steel hull. It is also difficult to apply the coating evenly. The thickness can vary from 750 microns to 2,000 microns.

The authors have noticed similar thickness variations on Arctic icebreakers.

Most of their coating application is done in the dry dock, rather than in the shop. However, on new ships, they will coat the hull in the shop in the areas where the keel blocks will touch the hull. They usually thin the Inerta 160 with acetone and apply the coating with a roller to these areas. They have inspected these areas after one year of service, and they are in good condition. This appears to be a good procedure for protecting the keel block areas.

(e) Transport Canada - Laurentian Region - Quebec City, P.Q.

Transport Canada was visited to obtain information from an owner of icebreakers that have had the low-friction hull coatings applied to them. Mr. J. Mondy is the Engineer Superintendent of Fleet Systems in the Laurentian Region for Transport Canada.

Generally, Transport Canada was pleased with the performance of the high-performance coatings. There have been problems, and these are noted in the following list of vessels. It should be noted that none of these vessels have impressed-current cathodic-protection systems to influence the performance of the coating.

1. CCGS Beauport

The Beauport was coated in August 1979 with the Inerta 160 coating. It was coated at Marine Industries Ltd. using a mobile shelter in poor weather. Marine Industries Ltd. had the capability of heating the shelter but had no method of controlling relative humidity other than by heating. It was reported by Marine Industries that relative humidity could be a problem.

The Beauport is a sounding ship and is not used for breaking ice. It was coated for corrosion protection at a cost of about $55,000. The surface area coated was about 700 sq m (7,530 sq ft).

The coating is in good condition, except for rust bleeding through small pinholes in the coating.

ii. CCGS Montcalm

The Montcalm was coated in September 1979 with Inerta 160 at Canadian Vickers. The Montcalm is a 1100 Class Light Icebreaker and is used as a buoy vessel. The Inerta 160 coating was applied to 1,200 sq m (12,900 sq ft) at a cost of $90,000.

The coating was inspected in June 1981 and was 95% intact. However, the damaged areas were repaired at a cost of $35,000 for 140 sq m (15,060 sq ft) of hull. In May 1983, it was inspected again and was still in good condition. The hull was badly corroded prior to coating, and the Inerta 160 bonded very well to the rough surface.

iii. CCGS Ville Marie

The Ville Marie was coated in May 1980 with Inerta 160 at Marine Industries Ltd. Approximately 390 sq m (4,200 sq ft) of hull were coated at a cost of $63,000. The hull was completely enclosed during the work with canvas. The weather was reported to be good. The relative humidity was not controlled. Heaters were available if temperatures were below 13°C (55°F).

The Ville Marie is a search-and-rescue cutter that was coated for corrosion protection only. The coating was checked in 1981, and many areas of low coating thickness were found. These areas were sandblasted and recoated. Because of the thinness of the coating, the repair was easy. The thin coating may have resulted from applicator inexperience in applying the Inerta 160.

iv. CCGS Montmagny

The Montmagny is a buoy vessel that has been ice strenghthened. It is used from March to December of each year in ice-free waters. It was coated at Marine Industries Ltd. in June 1981 for corrosion protection. No shelter was used during the work.

The hull is severely pitted, as can be seen in Photographs III-10 to 13. An area of the Inerta 160 coating that was damaged was inspected in May 1983 in the Marine Industries Ltd. yard. Photographs III-12 and 13 show the coating before and after it was lifted with a jackknife. The coating that was removed was not bonded to the steel. It is possible the coating never adhered properly to the steel (moisture, light rust on surface) and was susceptible to underfilm corrosion.

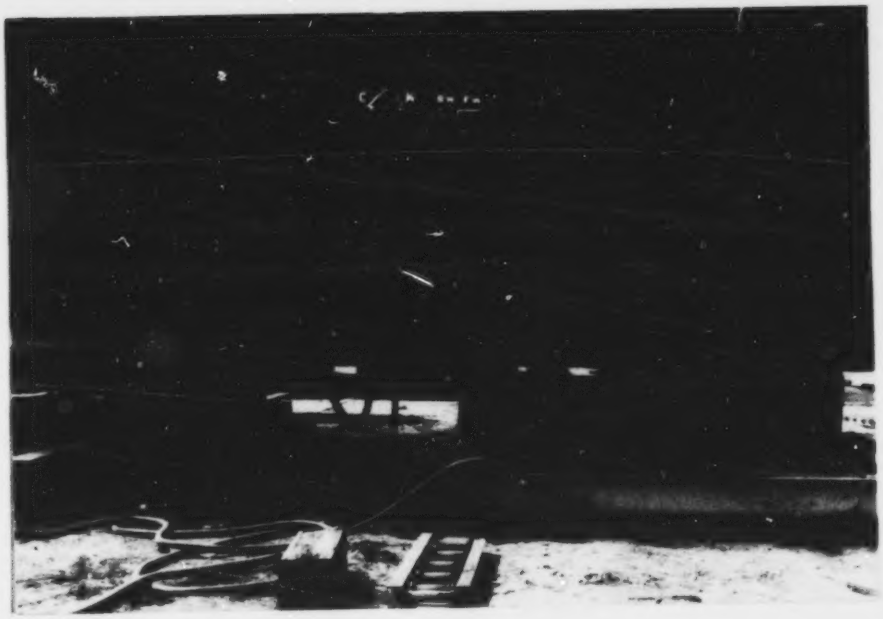
The original cost of the coating application was $65,000. Approximately 420 sq m (4,520 sq ft) of hull were coated.

v. CCGS Pierre Radisson

The Pierre Radisson is a 1200 Class Icebreaker (Arctic Class 3) that was coated with Inerta 160 in July 1982 at Halifax Industries. The cost of the coating application was $250,000. The surface area coated was 2,780 sq m (29,910 sq ft).

The coating was applied under a shelter constructed from polyethylene sheeting and scaffolding.

PHOTOGRAPH III-10 - INERTA 160 on CCGS MONTMAGNY



PHOTOGRAPH III-11 - DAMAGE TO INERTA 160 ON HULL OF CCGS MONTMAGNY

PHOTOGRAPH III-12 - CLOSE UP VIEW OF COATING DAMAGE

PHOTOGRAPH III-13 - UNDERCUTTING OF INERTA 160 BY CORROSION

The coating is in good condition above the water line. The condition of the underwater portion is unknown.

vi. CCGS Des Groseilliers

The Des Groseilliers is a 1200 Class Icebreaker that was coated by Port Weller Dry Docks in September 1982 with Zebron polyurethane.

It is reported that the Zebron coating has failed in the ice-belt area. Generally the areas of failure are larger than that normally seen on the Inerta 160-coated ships. See Section III.I.1.(c) above for application conditions.

(f) Societe des Traversiers du Quebec - Quebec City, P.Q.

The Societe des Traversiers du Quebec (STQ) owns and operates several passenger ferries along the St. Lawrence River. Three of the ferries have been coated with Inerta 160. They are as follows.

i. Camille Marcoux

Originally it was coated in October 1976 with Woolsey Res "N" Glass, a glass-flake, polyester coating. However, the coating application was rushed, and the ferry was placed in service prior to the coating completely curing. As a result, the coating system failed in many areas (75% of the coating was left) and was partially replaced in May 1978 with Inerta 160. The work was completed on 280 sq m (3,010 sq ft) of hull surface at Marine Industries Ltd. The entire ship was recoated in May and June 1979 with Inerta 160 on 1,670 sq m (17,970 sq ft) of hull. The cost for material alone was $30,000.

Touch-up work was done to the ferry in the fall of 1983. It was expected that 20% of the coating would require repairs.

ii. Jos Deschenes

The Jos Deschenes is a new ferry constructed in 1980. It was coated in March 1980 with Inerta 160 at Marine Industries Ltd. under a shelter. It was docked in September 1981 and had touch-up repair work done to the coating. Originally, 1,400 sq m (15,060 sq ft) of hull were coated. In 1981, only 50 sq m (540 sq ft) required touch-up (about 3% of the hull).

It was reported that the Inerta 160 coating was in poor condition in May 1983. It was to be redocked in October of that year and the coating inspected at that time. The Societe des Traversiers du Quebec were unable to release the results of the inspection for reasons of confidentiality.

iii. Armand Imbeau

The Armand Imbeau is similar to the Jos Deschenes. They were both built at the same time at Marine Industries Ltd. It was redocked in May 1981 and 45 sq m (480 sq ft) of Inerta 160 was repaired. Reportedly, it was having the same problems as the Jos Deschenes.

(g) Marystown Shipyard Ltd. - Marystown, Newfoundland

Two ships have been coated with the Inerta 160 at Marystown Shipyard Ltd. The CCGS Tupper was coated in July 1977 on 880 sq m (9,470 sq ft) of hull. Since that time, it has been redocked twice at other shipyards. In July 1979, 325 sq m (3,500 sq ft) of hull were recoated, and in November 1982, 465 sq m (5,000 sq ft) of hull were recoated at Marine Industries Ltd. The second ship was the CCGS Cape Roger, which was coated in July 1982. Eight hundred square meters (8,600 sq ft) of hull were coated with the Inerta 160.

The ships were cleaned by a crew of five men operating two sandblasting guns. In total, about 200 man-hours were required per ship.

The Inerta 160 coating was applied in one application 1,000 microns thick. In both cases, the weather was rainy and foggy, thereby, requiring the use of shelters. Wooden scaffolding and polyethylene sheeting were erected on one side of the ship and, after coating application was completed, were moved to the other side of the ship. It required about 100 man-hours to construct the shelter on each side.

There was no method for venting, other than a 76-cm high space beneath the keel between the keel blocks.

Two small electric heaters were installed to heat the shelter, but it is doubtful that the heaters were of much use.

Marystown Shipyard had no records of temperature and relative humidity during the work on either ship.

The ships were coated in about 16 man-hours using a single set of spray equipment.

Shelters are not normally used at Marystown Shipyard for conventional coating application. Shelters are used only for special coating work (such as required for the Inerta 160).

(h) Canadian Coast Guard - Maritimes Region - Dartmouth, Nova Scotia

The Canadian Coast Guard operates five icebreakers in the Maritimes Region.

i. CCGS Tupper

The Tupper was originally coated at Marystown Shipyard in 1977 with Inerta 160. According to Mr. K.C. Jones, Regional Fleet Engineering Superintendent in Dartmouth, N.S., for the Canadian Coast Guard, the coating has stood up well. It was recoated in November 1982 at Marine Industries Ltd. at a cost of $50,000 (465 sq m). Only the bow and water-line areas were recoated because of budget restrictions.

ii. CCGS Sir William Alexander

The Sir William Alexander is a Class-1100 Light Icebreaker originally coated with Inerta 160 in August 1977 at Halifax Industries Ltd. It was later recoated at Marine Industries Ltd. in November 1982. Originally 1,390 sq m (14,960 sq ft) of hull were coated.

In 1982, 465 sq m (5,000 sq ft) were recoated using a shelter constructed of scaffolding and plastic sheeting.

iii. CCGS Louis S. St. Laurent

The Louis S. St. Laurent is a 1300-Class Heavy Gulf Icebreaker. It was originally coated in December 1977 and January 1978 at Halifax Industries Ltd. at a cost of $120,000. The entire hull was coated, except for the midship bottom and a portion of the stern area (1,860 square meters).

Shelters were used during the coating application consisting of 2 x 4 wood boards laid between the top of the graving dock and the top of the ship and covered by plastic sheeting.

The ship was recoated in August 1982 at Saint John Shipbuilding & Dry Dock. No shelter was used because of good weather during coating application. The coating was in generally good condition with some damage. Areas where the coating was damaged were blast cleaned to bare steel. The existing coating was roughened by blasting and the entire hull was recoated. In total, 3,625 sq m (39,000 sq ft) of hull were coated with Inerta 160.

iv. CCGS Labrador

The Labrador was originally coated with Inerta 160 at a cost of $50,000* in July 1979. In total, 2,360 sq m (25,400 sq ft) of hull were coated. No shelter was used in coating the Labrador. The Canadian Coast Guard is pleased with the performance of the Inerta 160 on the

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*This cost may not include the cost of cleaning the hull.

Labrador. The ship has been used in ice in the Gulf of St. Lawrence, the Arctic, and in Newfoundland waters.

The coating has been touched up since 1979. The ship was redocked in 1981 at the C.N. dry dock in St. John's, Newfoundland, and it was redocked a second time in early 1983 at Davie Shipyard. The coating may have had touchup work done to it again.

v. CCGS John A. MacDonald

The John A. MacDonald is a Class-1200 Medium Gulf/River Icebreaker that was originally coated by Halifax Industries Ltd. in March 1980. The entire hull was coated with Inerta 160 in a graving dock using a shelter similar to that used on the Louis S. St. Laurent. Two thousand, six hundred square meters (27,980 sq ft) of hull were coated.

The Inerta 160 coating was repaired in early 1984 with Devran 288. Apparently, 90% of the Inerta 160 was removed from the ice line, while 10% was damaged on the bottom.

The repair involved sandblasting the existing Inerta 160, feathering its edge, removing all rust to a near-white finish, and applying 125 microns (5 mils) of Devran 288 to the existing Inerta 160 and 635 microns (25 mils) to the bare steel. The Devran 288 was applied in two coats.

After six months (some of it in ice), 98% of the Devran 288 was reportedly intact. There was slight abrasion damage at the bow, starboard side, and the rudder.

vi. CCGS J.E. Bernier and CCGS Tracy

Both the aforementioned vessels were existing supply-and-buoy ships constructed in the late 1960s. The Bernier is a medium icebreaker that is also used for search and rescue. The Tracy has light icebreaking capacity.

The ships were coated with Devran 288 in 1984. The Bernier was blast cleaned and coated at Versatile Vickers Inc. in Montreal, while Verreault Navigation Inc. coated the Tracy. The Canadian Coast Guard was contacted, but we were informed that the vessels had not been dry docked, and the coating condition was unknown.

(i) Canadian Marine Drilling Ltd. (Canmar)

i. Kigoriak

The Canmar Kigoriak was built in 1979 at St. John Shipyard. It is rated as a Canadian Class-3 icebreaker, and it performs supply-and-service functions in the Beaufort Sea. The engine power of the Kigoriak is 16,800 BHP.

The first dry docking occurred in December 1981. No coating had been applied to the hull, other than three small test patches at the bow, starboard side, and the thruster tunnels. Photograph III-14 shows the test patch during the June 1982 dry docking. Approximately 6 sq m (64 sq ft) of hull was coated with Inerta 160. At the December 1981 dry docking, the coating damage was estimated to be 15%. By June 1982, the damage had increased to 30%.

PHOTOGRAPH III-14 - CANMAR KIGORIAK DRY DOCKED IN McKINLEY BAY, N.W.T.

The test patch on the starboard side was 90% intact, with most of the wear along the leading edge of the patch.

The coating on the thruster tunnels was 80% to 90% intact. Canmar appeared to be quite pleased with the performance of the Inerta 160.

The entire hull was coated in August 1982. Prior to application, asperities in corroded areas were ground smooth, the hull was degreased and rinsed, and then blast cleaned to a near-white finish. The profile achieved was 60 microns to 90 microns (2.5 mils to 3.5 mils). The existing coating test patches were not removed. They were roughened and the edges feathered. In total, 2,400 sq m (25,800 sq ft) of hull was coated. The completed hull coating is shown in Photographs III-15 and 16.

By November 1984, it was estimated that the coating had been 5% to 10% damaged.

An impressed-current, cathodic-protection system was installed on the vessel in August 1982. No ill effects on the Inerta 160 coating resulting from cathodic protection are reported.

ii. Robert Lemeur

The Robert Lemeur is an Arctic Class-3 ice-breaking supply vessel that was built in Vancouver by Burrard Yarrows Corporation in 1982. It was designed based on the knowledge gained from the full-scale tests on the Kigoriak. It is smaller than the Kigoriak, and its engine power is 9,600 BHP.

PHOTOGRAPH III-15 - COATED BOW OF KIGORIAK

PHOTOGRAPH III-16 - COATED PORT SIDE OF KIGORIAK

The ship was cleaned and coated with Inerta 160 at Burrard Yarrows after construction was complete. The steel was blast cleaned with grit to a near-white finish, removing the existing shop primer. The surface profile was a minimum of 80 microns (3 mils).

One coat of Inerta 160 was applied 750 microns (30 mils) thick to 2,600 sq m (28,000 sq ft) of hull. The ship was shrouded with tarpaulins during blast cleaning and coating application.

After two years service, the Robert Lemeur was dry docked in McKinley Bay, N.W.T. Repairs were made to the coating at that time. Information was not available on the extent of the coating damage.

2. Finland

(a) Teknos-Maalit Oy

Most of the information procured from Teknos-Maalit Oy has already been discussed, but there are still several additional points worth mentioning

Generally, all vessels coated with the Inerta 160 system receive the coating over the entire hull. Their experience indicates coating costs are not reduced significantly by using a conventional paint system on the hull bottom. Broken ice pieces flow under the ship and abrade conventional paints. Inerta 160 applied in this area performs very well.

Antifouling has been applied to Inerta 160 while it is still uncured. It has been found that the bond between the two is improved when this is done. The

antifouling has a longer life, but the ice still removes it. It also does not solve the problem of applying antifouling to the fully cured Inerta 160 after it has been in service for several years. The coating is very hard, and subsequent coatings do not adhere well to it, even if the original coating is roughened by abrasive blast cleaning. This applies to second coats of Inerta 160 or antifoulings. The bond is only mechanical. A chemical bond does not develop.

Teknos-Maalit Oy recognizes the need for third-party inspection during the cleaning and coating operations. A conflict of interest arises when the coating manufacturer is the inspection agency. Apparently, several owners provide their own inspectors, and this eliminates any problems.

(b) Oy Henry Nielsen Ab

The shipping company of Oy Henry Nielsen Ab operates five vessels coated with Inerta 160. They are extremely pleased with the performance of the product. The use of Inerta 160 has decreased the frequency of dry docking from an annual basis to once every two to three years.

It has also reduced their fuel costs by lowering the resistance of the hull to both water and ice. The crews on the ships report that the vessels travel through ice much easier when coated.

Most of their vessels are ice-strengthened for travel through ice on their own. However, during severe winters, either assistance is received from icebreakers or two ships travel the same route together to broaden the channel.

Oy Henry Nielsen Ab has operated their vessels with the Inerta 160 for three winters (as of 1984). The Tebo

Star has been dry docked three times during this time, and the coating is reported to be in very good condition. The Shelltrans has been dry docked once, and the coating is also in good condition.

They point out that the following items are critical to the success of the system:

- Proper inspection of coating application is required, preferably by a third party;
- The coating must be applied under the proper conditions (temperature, relative humidity, etc.);
- The shipyard personnel must be properly trained when using Inerta 160.

(c) Oy Wartsila Ab

Most of the information from Oy Wartsila Ab has already been noted. However, there are several additional items that should be mentioned.

Often, the Inerta 160 coating is damaged by internal hull welding or by welding galvanic anodes to the hull. Teknos-Maalit Oy would prefer to have the shipyard install the anodes prior to coating application. This reduces the areas requiring coating repair. This is important since it has already been noted how difficult it is to repair Inerta 160. The anodes would require masking when the coating was applied if this procedure was followed.

(d) Finnish Board of Navigation

The Finnish Board of Navigation owns ten icebreaking vessels. All of them have been coated with Inerta 160. The Board is pleased with the performance of Inerta 160 and plans to use it on the new icebreaker, Karhu II.

The first vessel that was fully coated with the coating was the Karhu I. The Sisu was the first coated in 1976 with the present-day formulation of the coating. It has performed well, and the entire hull was recoated in 1982. Photograph III-17 shows the Sisu. It is the most powerful icebreaker operated by the Board at 16,180 kW (22,300 BHP).

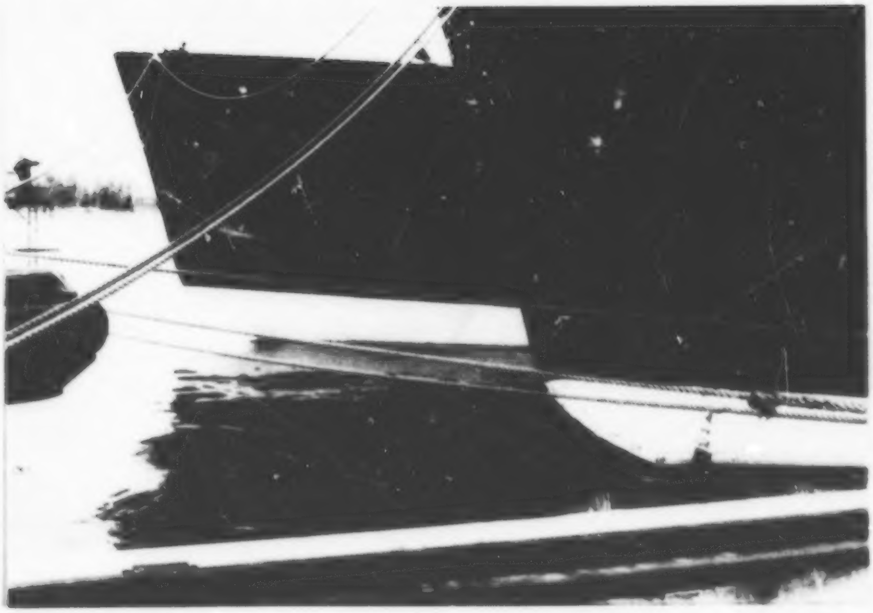
Photographs III-18 and 19 show the condition of the Inerta 160 along the ice line at the bow of the icebreakers, Karhu I and Hanse It appears to be in good condition other than some abrasion damage by the anchor

Photographs III-20 to 23 depict the condition of Inerta 160 on the hull of the icebreaker, Urho. The estimate of damage on the coating was 5% after three years service. The Urho originally was coated with Sigma, a solventless epoxy from the Netherlands, but it failed after only one season. In 1981, the old coating was removed and Inerta 160 was applied.

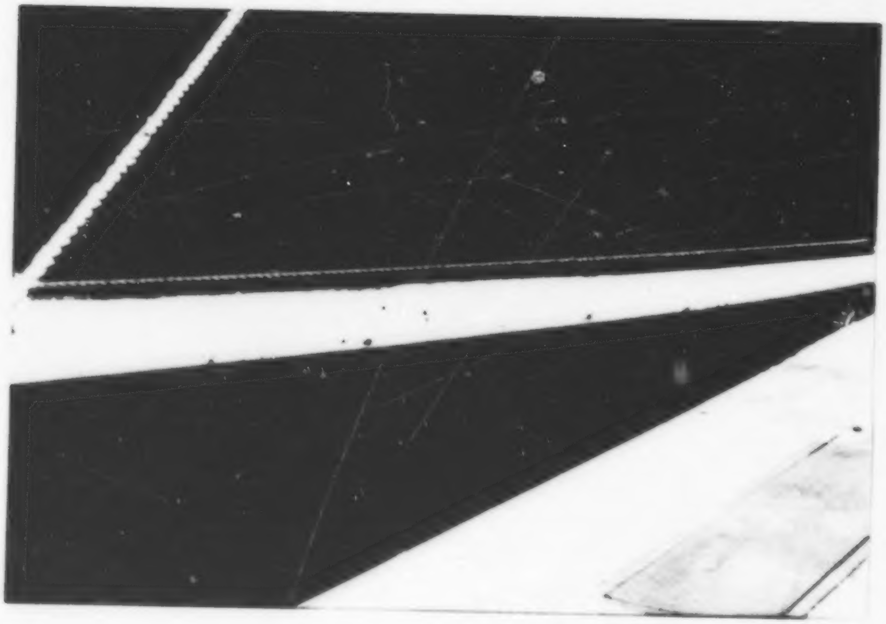
It should be noted that the discoloration on the coating is fouling Barnacles and weeds have attached themselves to the hull during the summer off-season. The barnacles were easily removed by scraping. They did not penetrate the coating.

The icebreaker, Hanse, is depicted in Photographs III-24 and 25. It is one of the smaller icebreakers operated by the Board (5,520 kW or 7,600 BHP). It is actually owned by the Federal Republic of Germany and is used by the Board during severe

PHOTOGRAPH III-17 - FINNISH ICEBREAKER, SISU



PHOTOGRAPH III-18 - CONDITION OF INERTA 160 AT ICE LINE



PHOTOGRAPH III-19 - CONDITION OF INERTA 160 ALONG ICE LINE OF HANSE

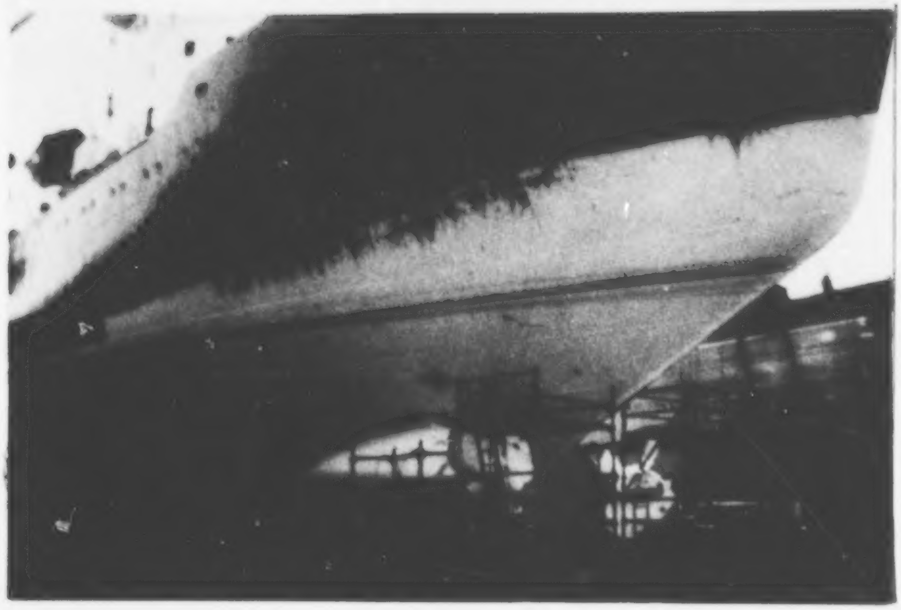
PHOTOGRAPH III-20 - ICEBREAKER, URHO, IN DRY DOCK AT VARMET SHIPYARD

PHOTOGRAPH III-21 - BOW OF URHO

PHOTOGRAPH III-22 - INERTA 160 ICE-LINE DAMAGE ON URHO

PHOTOGRAPH III-23 - COATING DAMAGE AT STERN OF URHO

PHOTOGRAPH III-24 - STERN OF ICEBREAKER, HANSE



PHOTOGRAPH III-25 - BOW OF HANSE

winters. The ship was coated with Inerta 160 filler and Inerta 160 to a thickness exceeding 500 microns in 1981.

The photographs were taken in 1983 after 1,800 h of icebreaking. The coating was in good condition, with less than 3% damage.

Photographs III-26 to 29 depict the condition of the coating on the icebreaker, Varma. Most of the damage is concentrated in the areas of worst ice abrasion and impact; the bow and the ice line. The damage shown in Photograph III-27 was caused by the ship running ashore.

When the photographs were taken in 1983, the ship had undergone icebreaking for four winters, a total of 4,900 h. The damage to the Inerta 160 was estimated at 10% to 15% at the bow and ice line and less than 3% elsewhere. To repair these areas, Inerta 160 filler and a top coat were used after blast cleaning to a near-white finish.

There was more coating damage on the Varma than on the Hanse, but this can be explained by the length of service and the engine power. The Varma is rated for 8,830 kW (12,200 BHP), which means that it has the ability to travel through thicker ice or the same ice conditions at a higher speed.

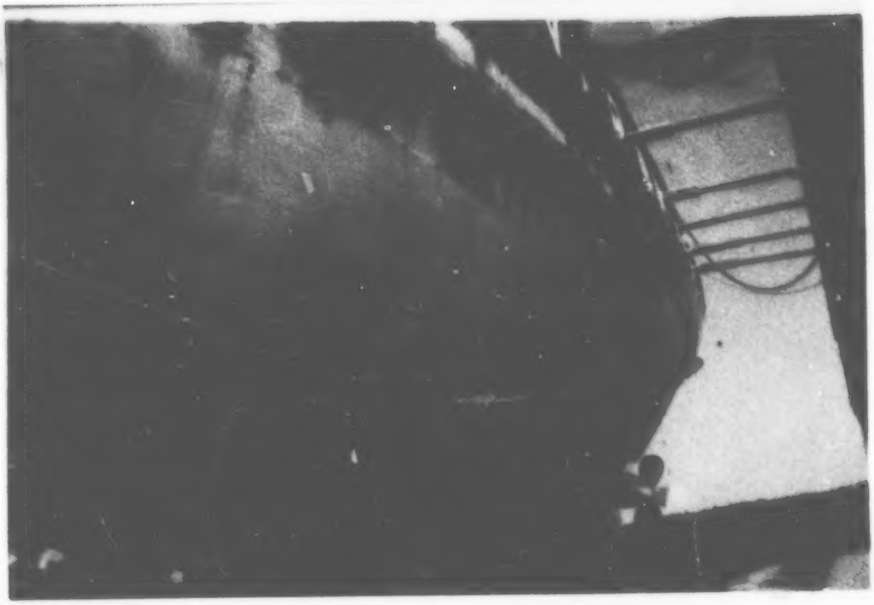
The Board presently dry docks the icebreakers after every second season. Divers inspect the hulls annually for structural and coating damage. The white colour of the Inerta 160 makes this task much easier.

Small damaged areas are not normally repaired. If the small areas are repaired, a lessexpensive, conventional coating is used such as International Paints' Intertuf vinyl. This does not withstand ice abrasion, but it does protect the hull during the summer months. The Board now plans to recoat the icebreakers with Inerta 160 every five years. This is a substantial

PHOTOGRAPH III-26 - BOW OF ICEBREAKER, VARMA

PHOTOGRAPH III-27 - STARBOARD BOTTOM OF VARMA

PHOTOGRAPH III-28 - PORT-SIDE BOTTOM OF VARMA



PHOTOGRAPH III-29 - PORT-SIDE MIDSHIP ICE LINE OF VARMA improvement over the conventional paints where hull recoating was required annually.

The Board has noted an approximate 10% decrease in fuel consumption since coating the icebreakers with the Inerta 160.

It is estimated that the fuel saving for a large ferry would amount to 4 million mks/yr ($900,000/yr). This assumes fuel costs of 8,000 mks/h ($1,800/h) and a saving of 10%. A ferry typically operates 5,000 h/yr. This cost saving would more than offset the cost of coating the hull with the Inerta 160. One of the large passenger ferries that is coated with Inerta 160 is shown in Photograph III-30.

With the Inerta 160 coating and impressed-current cathodic protection, the Board is no longer concerned about corrosion. Previously, the welds had to be rewelded approximately every ten years. The coating and cathodic-protection system have complemented each other on the icebreakers.

On the new icebreaker, Karhu II, the Board is trying 316 stainless-steel cladding 3 mm to 4 mm thick (0.12 in to 0.16 in) at the ice line instead of Inerta 160. The cladding would be 1.6 m (5.2 ft) wide and would extend the entire length of the ship. Inerta 160 would still be used on the icebreaker bottom and other areas below the cladding

3. United States

The majority of the work done in the United States has been conducted by the United States Coast Guard (USCG), beginning with the work by S.J. Calabrese. In recent years, the work has involved full-scale tests on icebreakers coated with Inerta 160. LCDR Dennis M. Egan, was contacted by our

VIKING LINE

PHOTOGRAPH III-30 - VIKING LINE PASSENGER FERRY office in March 1983, and information was procured based on his operational experience. Mr. Egan accompanied the USCG icebreaker, Northwind, on three voyages to the Antarctic and four voyages to the Arctic. Subsequently a paper was published from the spring meeting of the STAR symposium in Washington on April 6 to 9, 1983(42). The following has been extracted from this paper and private correspondence with Mr. Egan (49).

The icebreaker, Northwind, was not involved with the original research conducted by S.J. Calabrese; however, based on the results from the study, it was decided in 1980 to coat the hull with Inerta 160. The icebreaker, CGC Glacier was coated with both the Zebron and Inerta 160 [see Section III.C.3.(a)] in 1977. After 168 h of icebreaking, both coatings were in good condition; however, the entire hull of the CGC Glacier was not examined, and the Zebron did exhibit intercoat delamination. The CGC Glacier was then deployed to the Antarctic, and the Inerta 160 out-performed the Zebron. Based on these results, the USCG apparently decided to use Inerta 160 on the Northwind because of the inability to apply the Zebron in a consistent and dependable manner. It was also applied to the CGC Polar Sea, CGC Polar Star, and several new Coast Guard domestic-class icebreakers. Reports from these vessels indicate the coating's resistance to ice damage is outstanding.

Mr. Egan conducted a program to improve the Northwind's fuel conservation without any reduction in operational performance during the period 1980 to 1982. Besides coating the hull, two other methods were used to reduce fuel consumption:

- A small auxiliary steam generator was salvaged, rebuilt, and used for steam production while in port instead of using the ship's larger generators;

- The minimum number of engines was used in open-water transit, during icebreaking and during scientific operations requiring station keeping.

Over a period of one and one-half years, the fuel consumption was reduced by 605,000 L (160,000 U.S. ga). Of the total, 510,000 L (135,000 U.S. ga) could be attributed to the coating. The total saving represented a 14% reduction in fuel consumption. It was estimated that the coating will have paid for itself in fuel savings alone in approximately two years.

The coating also decreased the power required to operate in 3 to 6-foot-thick ice floes. In 1972, four 1,470-kW (2,000-BHP) diesel engines were required. In 1980, after the Northwind was re-engined in 1974, only two 2,200-kW (3,000-BHP) engines were required to handle the same 3 to 6-foot-thick ice floes.

The USCG vessels have also experienced extensive weld corrosion (up to 30% of the shell plate thickness was lost) Instead of rewelding the welds were filled with Inerta 160. After two years and extensive Arctic icebreaking, the coating was 95% intact, and the weld corrosion appeared to be arrested. Mr. Egan estimated that the lifetime of Inerta 160 is at least eight years, with only periodic touch up of local coating damage. This was based on his experience with the Northwind and observations of hull coatings on other icebreakers.

The Inerta 160 does foul heavily when not in service. The fouling eliminates all fuel efficiencies gained from the smooth, low-friction surface. The only answer they have to overcome this problem is underwater cleaning to remove the fouling. The boring organisms could not penetrate the coating's hard surface; therefore, it could be easily cleaned.

The application of the Inerta 160 coating to the Northwind stressed the importance of the following:

- The coating must be applied under proper conditions; that is, a shelter should be used;

- It is imperative that the steel receive superior cleaning (near-white finish);

- Many of the shipyards do not have the experience or expertise to properly apply Inerta 160. They must be augmented by personnel from International Paints, and it is reported even some of their staff may not have the technical expertise to properly apply Inerta 160;

- The work must be inspected by personnel other than the coating manufacturer's;

- The coating must be allowed to cure completely before entering the water; otherwise, premature failure will occur.

It was also noted that the Zebron polyurethane could be superior to the Inerta 160, if the manufacturer could overcome application difficulties. Properly applied, Zebron has a higher adhesive strength and a lower coefficient of friction than does Inerta 160.

4. Great Britain

The following companies were contacted in Great Britain.

(a) International Paints

Abrasion-resistant coatings for service in ice-covered waters receive very little interest in Great Britain. Some have been used in the North Sea drilling platforms; otherwise, very little has been used on ships.

For ships trading intermittently in ice, such as the paper/pulp carriers that travel from Scandinavian countries to the east coast of Canada, International Paints has used Intershield in two or three coats. It is recommended for intermittent, light ice conditions only It has apparently performed well on the Corner Brook, a Ro-Ro vessel owned by Sig Bergesen d.y. and Co. of Norway. The Intershield was 99% intact on the bow after 25 months. Five months of every year is spent travelling in ice-covered waters.

The kinetic coefficient of friction is higher for the Intershield than for the Inerta 160 (0.25 and 0.10, respectively)

The optimum coating thickness for the Intershield EG series epoxy is 300 microns (12 mils). Impact resistance decreases at thicknesses greater than this value.

The applied cost of the Intershield in Great Britain is 3 Pounds Sterling/sq m ($0.80/sq ft). These prices were based on April 1984 costs in Europe. By comparison, the cost to apply the Inerta 160 in Great Britain is approximately two-thirds higher. Therefore, the Intershield may be a lower cost alternative where ice conditions are light.

International Paints states that shelters are seldom used in Great Britain. Temperatures are not extreme and relative humidity is generally not a problem from April to September. Dry docking is usually scheduled for this time period. If Intershield is applied during the winter months, the owner is made aware that delays may occur because of weather.

The shipyards are not setup to construct shelters, and therefore, they are costly and the yards avoid them.

(b) British Ship Research Association

The British Ship Research Association (BSRA) has not conducted research into abrasion-resistant coatings for ice. They stated that the Ministry of Defense Naval Research Laboratory has been downgraded and has only a skeleton of its former self. They are doing very little coating research and testing.

The BSRA confirmed that the British shipyards do not use shelters during paint application.

(c) National Corrosion Service

The National Corrosion Service is not involved with any research into coatings for use on ships in ice-covered waters. The only work related to this topic involves coatings that they have found to work well on the drilling rigs in the North Sea. Mebon Coatings produces Bonguard 100CP, a polyurethane pitch elastomer which has been used for the protection of seabed anchor connections where impact and water resistance is required. It also has been used as a dielectric shield around anodes because of its high dielectric strength and resistance to cathodic disbonding. It has not been used in ice. The other coating is Bonslip F which has been previously discussed.

IV. CATHODIC PROTECTION

A. THEORY OF CATHODIC PROTECTION

1. General

Cathodic protection is used for protection of pipelines, marine structures, ships, tank bottoms, foundation pilings, and the like, where a metallic (usually iron and steel) structure is immersed in an electrolyte which is corrosive to the metal In this report, discussions of cathodic protection are confined to ships in seawater or possibly in brackish water. The material in Sections IV.A and B applies to vessels operating in any seawater. The application of cathodic protection to ice-going vessels is presented in Sections IV C through F following.

2. The Mechanism of Cathodic Protection

Corrosion control by cathodic protection depends upon the polarization of a metal surface (steel for ships) by an externally impressed direct current, i.e. conventional direct-current flow is from an external electrode through the seawater onto the metal to be protected. In the cell so set up, the metal (ship) is the cathode, and current flows from an external anode. Because the metal being protected by polarization is the cathode in the cell, the process is called cathodic protection.

Various descriptions and definitions of cathodic protection have been presented. In essence, the function of the impressed current is to polarize all surfaces of the metal to a uniform value so that no local corrosion cells will operate. To achieve this, at a minimum, it is necessary to polarize the cathodic (noncorroding) areas on the metal to the open-circuit potential of anodic (corroding) areas. Polarization beyond this point does no harm to steel, though it is wasteful of electric power (or galvanic anode metal), and there may be some danger of hydrogen charging of certain high-strength steels if the hydrogen overpotential on steel is exceeded.

Polarization is primarily a function of current density on the metal being protected, though the ultimate level of polarization is limited by the potential of the anode from which the polarizing current flows. Thus, a zinc galvanic anode can not polarize a metal surface beyond about 1.1 volts negative to a silver/silver-chloride reference cell because that is its own solution potential A magnesium anode can polarize metals to about 1.55 volts, and there is theoretically no limit to the polarization available from an electrically powered, impressed-current system.

The electrochemical reactions involved in a cathodic-protection system are important in preparing system designs. These are shown below.

(a) At the Cathode - Steel Hull

- Generation of hydroxyl (OH) ions with a resulting increase in alkalinity at the metal surface up to a potential of about 1.20 volts negative to a silver/silver-chloride reference electrode.

- Generation of hydrogen gas at the hydrogen-evolution potential on steel, about 1.20 volts negative or greater.

(b) At the Anode

- Using galvanic anodes, dissolution of metal ions.
- Using noble-metal, impressed-current anodes, chlorine and oxygen evolved, and some metal ions may also be produced, depending upon the anode composition.

3. Criteria for Cathodic Protection

Various methods for defining when cathodic protection is achieved have been presented. The commonly accepted criterion is polarization to a potential 0.80 volts negative to a silver/silver-chloride reference electrode or 0.25 volts positive to a zinc reference electrode. Since seawater is a relatively conductive electrolyte, there usually is not sufficient IR drop in the liquid part of the measuring circuit to affect the correctness of a polarized potential reading. In certain cases (low-conductivity water), it may be desirable to use the on-off method recommended for measuring potentials of underground structures where the IR drop in the soil can lead to serious errors in the potential readings.

The standard reference electrode normally used in seawater is the saturated silver/silver-chloride half cell. Other electrodes may be used, but the copper/copper-sulphate cell should never be used because of precipitation of cuprous chloride within the cell.

To conduct a potential survey of a cathodically protected vessel, the reference electrode is positioned at various points near the hull and the potential difference (so-called polarized potential) is measured with a potentiometer or a very high-resistance voltmeter. The reference electrode "sees" that portion of the hull near to it, and so, a reference cell in one position can not indicate the condition of an entire hull. Therefore, it is common practice in controlling cathodic-protection systems to have more than one reference cell at those points which are likely to receive least protective current. On a well-coated hull, the use of a single reference cell results in better overall potential measurement than on a bare hull.

At a potential of 0.80 volts negative, steel in seawater ceases to corrode. It is not necessary (though it is desirable) to reach this potential to obtain some reduction in corrosion. Thus, if a hull is at, say, 0.75 volts negative, a significant reduction in corrosion will occur.

4. Current Density for Cathodic Protection of Vessels

The current density required for effective polarization depends upon the metal being protected, the composition and temperature of the water, the velocity of water relative to the hull and the amount of bare metal exposed. Bare steel in normal seawater is polarized to full protection at 75 ma to 120 ma per sq m (7 ma to 11 ma per sq ft), while copper and copper alloys require about 500 ma per sq m (50 ma per sq ft).

On a coated ship, the current density for protection depends upon the coating quality, the amount of bare steel, and the amount of other bare metals which may be connected to the steel hull. A very good coating system may initially lower the current requirement for polarization by a factor of 10 to 100, but as the coating deteriorates with time, the current requirement rises.

A bare propellor and propellor shaft on a well-coated hull may draw the majority of the initial protective current. This situation exists whether the shaft is directly connected to the engine or is connected to a reduction gear. With the ship at rest (engine not running), the propellor and shaft are part of the hull as far as the cathodic-protection system is concerned. With the engine running, the oil in the reduction gear insulates the propellor and shaft from the hull, but current may still flow onto these elements, along the shaft and jump to the hull in the stern tube, leading to corrosion of the shaft. It is normal to bond shafts to hulls by slip rings or special brushes to avoid such damage.

5. Formation of a Calcareous Coating

Because cathodically protected metal surfaces become slightly alkaline through the formation of hydroxyl ions by the cathode reaction, some of the dissolved elements in seawater may be precipitated. Magnesium and calcium hydroxides are precipitated initially, in time, converting to the carbonates. This formation of a "calcareous" deposit is common on bare steel in seawater and may be only a thin, almost invisible film or a heavy white deposit several inches thick, depending upon current density, water velocity, etc. It is common practice when protecting bare steel structures to initially apply a high current density to build up such a coating, which acts to reduce subsequent current requirements for polarization.

6. Effects of Cathodic Protection on Coatings

A good coating system reduces cathodic-protection current requirements and promotes throw of current from individual anodes to more remote hull areas. However, near an anode, the current density may be high enough to produce considerable alkalinity. Such alkalinity may attack certain paints, notably those based on natural-drying oils, leading to paint failure. In general, superior coating systems are not prone to such damage because of their inherent chemical resistance and because a hull with a good coating system does not require a high current density for polarization (hence, little alkali is generated).

If a vessel is polarized beyond 1.20 volts negative to a silver/silver-chloride half cell, hydrogen gas is produced at the hull. Because this gas is generated beneath the paint, it may generate sufficient pressure to blow the coating off the hull. Because of this danger, it is normal to limit hull potentials to numerical values more positive than 1.20 volts negative. It is common to see paint stripping near to impressed-current anodes or near the magnesium galvanic anodes where the shield is not adequately large to throw the current well away from the anode.

Coatings and cathodic protection are complementary methods for controlling corrosion on vessels. Each by itself can protect a vessel, but coatings deteriorate with time, and cathodic protection of a bare hull is costly. A good coating system operating with a cathodic-protection system offers optimum protection. Cathodic protection prevents corrosive attack at defects in the coating or at areas where abrasion or mechanical impact have removed the coating. Cathodic protection also prevents undercutting of the coating at damaged areas and, so, prolongs the usefulness of the coating. The coating, in turn, markedly reduces the protective current density and permits a relatively simple cathodic-protection installation to protect a hull.

It is appropriate to re-emphasize that cathodic protection can prevent corrosion completely on any submerged hull metal or even on those areas of the hull which are wetted 50% of the time. Thus, it is an essential component in any corrosion-control system for a seagoing vessel.

B. APPLICATION OF CATHODIC PROTECTION TO MARINE VESSELS

Subsequent sections deal with cathodic protection of ice-going vessels specifically. This section presents factors to be considered in the design and operation of a cathodic-protection system and with the more-common system types.

1. Factors to Consider in Design

(a) The system must have adequate capacity to polarize the hull under all conditions of operation and to protect bared areas resulting from coating damage.

(b) The system must have control flexibility so that the coating is not damaged by over polarization.

(c) Any coating system, including antifouling paint, must be selected to withstand the alkali generated by cathodic protection. Cathodic protection does not control marine fouling, except near impressed-current anodes.

(d) The area of bare propellor(s) and shaft(s) must be considered in determining current requirements, and shafts must be protected against "stray-current" damage.

(e) All components should be rugged to resist the inevitable impact of ice, logs, and debris found in seawater.

(f) All components should be capable of easy replacement without dry docking, or redundancy should be provided for the situation where one component is destroyed.

2. General Methods of Cathodic Protection

(a) By Use of Slung Anodes

Ships which are at rest much of the time can be protected most readily by using either galvanic or impressed-current anodes slung over the ship's side or suspended from the ship's berth. Such systems provide excellent current distribution, do not require hull attachments, can be replaced easily, and are low-cost. Typically a negative cable is disconnected when the ship is used, during which time, no cathodic protection exists. Mothballed naval vessels are protected by such systems.

The P and O vessels used a trailing aluminum wire for cathodic protection. As the wire was consumed, additional wire was reeled out. The system, while apparently simple and inexpensive, has not been used generally.

(b) By Use of Attached Galvanic Anodes

Galvanic anodes are used most commonly on smaller vessels where current requirements are low or on such vessels as barges where an electric power source is not available. A common problem with such systems is the tendency to underestimate the number of anodes needed to protect a vessel when the coating system has deteriorated.

Such anodes are usually placed low on the hull and toward the stern to minimize damage from debris. However, this concentration of anodes leads to poor current distribution, commonly with corrosion proceeding in the bow area.

Galvanic anodes can be attached by welding their steel cores to the hull or by fastening them through studs permanently attached to the hull. Magnesium anodes usually are placed on shields which may be sheets of rubber bonded to the hull or special heavy paints. All such anodes add to hull friction and are a constant maintenance item during dry docking, when old partially consumed anodes have to be removed and new ones installed. A common occurrence is for shipyard workers to paint the anodes when the hull is being painted, reducing anode effectiveness until the paint film is lost (and with inadequate cathodic protection in the interim)

i. Advantages of Galvanic Anodes

- Self-controlling, no need for reference electrodes, etc.;
- Amenable to redundancy to cover loss of anodes;
- If properly chosen, will not overprotect a hull;
- Do not require skilled staff for replacement.

ii. Disadvantages of Galvanic Anodes

- Generally, not adequately flexible in output to provide major extra protective current when a coating is badly damaged;
- They project from the hull and add to hull drag;

- They can be replaced at dry docking only;
- Replacement must coincide with dry docking, at which times, anodes with some life remaining have to be replaced to ensure protection in the period between dockings.

(c) By Use of Attached Impressed-Current Anodes

Impressed-current anodes typically are made from noble or seminoble metals which either do not dissolve or dissolve very slowly as electric current discharges from them. The favoured materials for ships in seawater are the true noble metals such as platinized titanium and the seminoble lead-silver alloy. Materials such as silicon iron, magnetite, and graphite have been used, but poor physical properties and limitations on current density precluded their wide use.

Because such anodes are used with high current outputs, there always is a danger of high alkalinity next to them. In addition, because they operate at relatively high voltage, they generate chlorine gas which can accumulate in recesses and cause corrosion. Anode holders must be carefully designed to overcome these problems and to protect the anode itself.

Impressed-current systems require a reliable power source on the ship and a means for controlling current output to maintain a protected potential. While such systems may be automated, they require trained personnel for effective operation and maintenance. They represent a much more sophisticated system than the galvanic anode.

i. Advantages of Attached Impressed-Current Systems

- Wide range of current output available;

- Current output can be controlled manually or automatically to suit demand;

- Few anodes are needed and, so, do not offer hull drag;

- In many systems, the components can be replaced with the ship underway.

ii. Disadvantages of Attached Impressed-Current Systems

- High local current density may lead to paint damage;

- Operation and maintenance requires technically trained personnel;

- Anodes and reference electrodes are subject to damage and require elaborate protective housings.

C. DEVELOPMENT OF CATHODIC PROTECTION FOR SERVICE ON ICE-GOING VESSELS

The original cathodic-protection systems that were used in ice-covered waters consisted of galvanic anodes, either magnesium or zinc. In other words, ships trading in ice were treated no differently than ships in ice-free waters. The only difference was the placement of the anodes on the hull.

In 1957, Canadian National Railways (CNR) realized the importance of cathodic protection of ships travelling in ice-covered waters(35). The MV Bona Vista was one of 25 coastal vessels and ferries operated by the CNR in the waters off Newfoundland. It was dry docked after one year's service, including two months in ice, and heavy hull corrosion was found. Most of the corrosion was concentrated at the welds, where pitting was as deep as 1/8 in (3.2 mm).

The decision was made to cathodically protect the hull using a controlled magnesium anode system. Half the magnesium anodes were mounted on the bilge keels toward the bow, and half were stud-mounted flat to the hull in rows toward the stern. The anodes were not welded or bolted directly to the steel hull, instead, they were electrically isolated, and contact was made through electrical cables. Anode leads were connected to collector cables midway in each anode group. The collector cables were fed through the hull and electrical current flow was controlled by a variable resister. The collector cable was protected by a half section of heavy-walled steel pipe welded to the hull.

Controlling the current flow extends the life expectancy of the magnesium anodes. This is advantageous if it is known that the anodes will last through several winters in ice. If conditions are too severe, and it is known that the anodes will be removed after only one season, no advantage is gained by controlling the current, and the anodes should be welded directly to the hull.

The system functioned well for two years; however, deficiencies were noted. Ice damage occurred at the connection between the anode lead and the collector cable. Ice damaged the bilge-keel-mounted anodes more readily than the flat-mounted anodes. No changes were made to the system, and it was renewed for another two-year period. Similar difficulties were encountered during this period.

A third system was installed, but instead, all anodes were mounted flat to the hull. In addition, a shield was used to protect the anode leads and the collector cable. After one season, the system was operating satisfactorily with no major problems.

Based on their experience with this vessel and other ferries breaking ice, they concluded the following:

- Vessels operating in ice can be successfully cathodically protected;
- The type and design of the cathodic-protection system depends upon the design features of the vessel, the severity of the ice conditions, and the duration of time in which the vessel operates in ice;
- It is more economically feasible to install test anodes at various locations on a vessel's hull to determine the best location for the anodes during the ice season;
- Where ice conditions are so severe that anodes can not be maintained on the hull during the ice season, an uncontrolled system (anodes connected to the hull directly by welding or studs) coupled with an effective paint system will provide complete corrosion protection in the ice-free season;
- A controlled system is best if ice conditions are not severe, and the anodes can be maintained the entire year;
- Anodes should be mounted flat to the hull as close to the stern as the current distribution will allow;
- Tapered ends on the anodes reduce ice damage;
- Special protection is required for the anode leads and collector cables;

- In uncontrolled systems where it is known that the anodes will not last through the winter, it is best to dry dock the vessel immediately after the end of the ice season for painting and anode installation to take maximum advantage of the protection over the ice-free period.

The majority of the vessels travelling in ice up to the mid-1970s had either no cathodic-protection system, and corrosion repairs were made to the hull during dry dockings, or zinc anodes or magnesium anodes were used as noted on the CNR M.V. Bona Vista. Owners were prepared to either repair the hull, including filling the welds with new metal, or replace the galvanic anodes every one or two years. Impressed-current cathodic-protection (ICCP) systems were infrequently used on ships trading in ice, unless ice conditions were not severe and the ship traded intermittently in the ice. Morgan reports that ICCP systems were used on ships in ice in the 1960s and 1970s(43). However, it is probable that the early installations did not seriously address the ice problem, and damage resulted on these systems.

The practice of the Canadian Coast Guard has been to install galvanic zinc anodes in the stern area of the icebreakers or use no cathodic protection. The use of zinc anodes at the stern was done to counter bimetallic corrosion problems (bronze or stainless-steel propellor, steel hull plate, steel forgings, or castings).

The first impressed-current system used on the Canadian Coast Guard vessels was the Cathelco System by Electrolyte Marine in Victoria, B.C. The system was used on the Pierre Radisson, but is used more for fouling prevention (the anodes generate chlorine gas which kills marine organisms) than corrosion prevention on the seabays.

Similar experience was encountered in Finland. Impressed-current was not used on icebreakers until the mid-1970s, and even then, it was still in the experimental stage.

The first serious work done on cathodic protection in ice using impressed-current was the Shell Oil offshore platforms at Cook Inlet, Alaska, in 1964(44). The environmental conditions are severe and are similar to the conditions experienced by icebreakers:

- Low water temperature: -1°C (30°F);
- High oxygen content (the water is apparently saturated with oxygen to the ocean floor all year);
- Rapid currents at 6 knots to 8 knots (high velocity of the vessel in the case of an icebreaker);
- Scouring action by water, with a high dissolved-solids content (greater than 20,000 ppm) and glacial silts in amounts up to 700 ppm;
- Moving ice floes that are 1 ft to 2 ft thick (0.3 m to 0.6 m).

Because of these conditions and the tidal range, corrosion rates of 890 microns per year (35 mils per year) were measured. The pitting corrosion rates were even higher, ranging from 2 mm to 2.5 mm (80 mils to 100 mils) per year. To eliminate the problem, it was decided to install an ICCP system. Galvanic anodes could not be used because of the very high current densities required to cathodically protect the steel. The offshore operations along the Gulf Coast indicated that 54 to 75 milliamperes per square meter (5 to 7 milliamperes per square foot) is needed for protection. Since the corrosion rates were higher in the Cook inlet, a higher current density would be needed for protection.

Initially, current densitites of 269 milliamperes per square meter (25 milliamperes per square foot) were tried. Complete protection was achieved using lead-silver alloy anodes mounted on remote concrete sleds on the ocean bottom. Anodes mounted on the platform legs were also tried; however, current distribution was poor. The potential decreased rapidly with increasing distance from the anode.

Following the initial work done by Shell Oil Co., 13 other platforms were installed between 1964 and 1968. Atlantic Richfield Co. constructed two platforms in the area and conducted their own ICCP design studies(45). Using leg and sled-mounted anodes, adequate protection was achieved at current densities of 538 milliamperes per square meter (50 milliamperes per square foot) for adequate current distribution and 380 to 430 milliamperes per square meter (35 to 40 milliamperes per square foot) for long-term protection.

All the anodes were installed below mean low tide to avoid damage from ice. The leg anodes were mounted on large dielectric shields consisting of coal-tar epoxy, 4.3 m by 3.2 m (14 ft by 10.5 ft). Current was supplied to the anodes by multiple rectifier units each rated for 200 amperes to 300 amperes.

Other researchers subsequently found that impressed-current densities of 970 to 1,080 milliamperes per square meter (90 to 100 milliamperes per square foot) formed a calcareous deposit on the platform legs(46). At densities of 430 to 650 milliamperes per square meter (40 to 60 milliamperes per square foot), the deposit deteriorates and does not form at densities less than this. It was observed that the deposit began to form in the spring after the ice was gone, but would be removed in the winter by ice abrasion.

The Cook Inlet experience undoubtedly provided assistance to those researchers studying the problem of applying cathodic protection to icebreakers. The researchers now at least knew the approximate current densities that could be expected to protect the steel hulls. The major problem that remained was how to install the ICCP anodes so that ice damage would be minimized.

This problem was studied by Corrintec International (formerly Morgan Berkeley) and Seppo Ylasaari of Cormet Oy beginning in the mid-1970s on the Finnish icebreakers owned and operated by the Board of Navigation. The first impressed-current system installed was on the icebreaker, Sampo, in 1978. The system consisted of two pairs of recessed anodes at the bow and the stern and one pair of reference electrodes in the middle of the ship. The icebreaker was coated with Inerta 160 on its hull.

With the success of the ICCP systems in Finland, several Canadian Coast Guard and the Arctic Class icebreakers operated by Beaudril and Canmar have been equipped with systems by Corrintec International or Wilson Walton International.

D. GALVANIC ANODES IN ICE

1. Composition and Operating Data

The typical composition of the zinc and aluminum anodes used in seawater is shown in Tables IV-1 and 2. Magnesium anode data has not been included, since the material is now rarely used in seawater because of its high consumption rate.

The primary difference between zinc and aluminum anodes is the current production efficiency. Per pound of material, the aluminum anode has a higher ampere-hour capacity than the zinc. This means that to produce the same amount of current for a given number of years the aluminum anode can be made smaller than the zinc anode. The smaller anode would also add less resistance to the hull when travelling through water or ice.

2. Typical Arrangements

Photograph IV-1 shows the typical anode arrangement at the stern of the Canmar Explorer II, a drillship used in

TABLE IV-1

ZINC ANODE DATA

SEAWATER USE

ALLOYING ELEMENT	SPECIFICATION	
	MIL-A-18001H (% composition)	ASTM B418-73 TYPE 1 (% composition)
Aluminum	0.10 - 0.50	0.10 - 0.40
Cadmium	0.025 - 0.15	0.03 - 0.10
Iron, maximum	0 005	0.005
Lead, maximum	0.006	0.003
Copper, maximum	0 005	---
Silicon, maximum	0.125	---
Zinc	remainder	remainder

Operating Data

Energy Capability: 820 ampere-hours/kg.
370 ampere-hours/lb.

Consumption Rate: 10.7 kg/ampere-year.
23.7 lb/ampere-year.

TABLE IV-2

ALUMINUM ANODE DATA

SEAWATER USE

ALLOYING ELEMENT	TYPICAL COMPOSITION (%)
Zinc	0.35 - 0 50
Silicon, maximum	0 10
Mercury	0.035 - 0.048
Indium	----
Aluminum	remainder

Operating Data

Energy Capability:	2,820 ampere-hours/kg. 1,280 ampere-hours/lb.
Consumption Rate:	3.1 kg/ampere-year. 8.8 lb/ampere-year.

PHOTOGRAPH IV-1 - ALUMINUM ANODES ON CANMAR EXPLORER II offshore oil and gas exploration in the Canadian Arctic. The aluminum anodes are welded to the rudder and the stern to protect those areas and the propellor from corrosion.

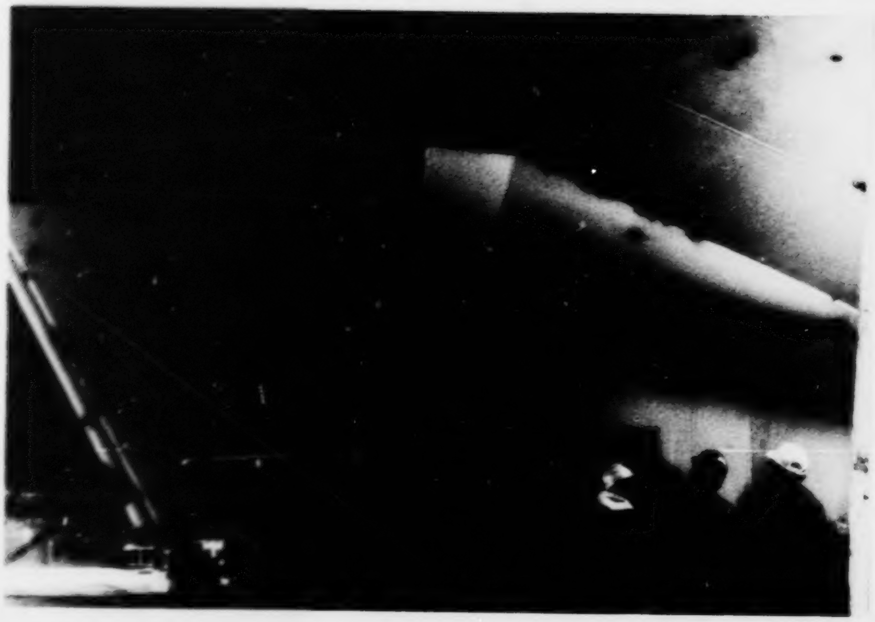
It should be noted that fairings have not been used around the anodes. Even with the use of fairings to protect the anodes, ice can remove them. Photograph IV-2 shows anodes missing from the stern of an Arctic icebreaker. Fairings were installed on either side of the anodes. The anodes were bolted to the steel; however, the studs had been sheared off by the ice.

Another type of galvanic anode installation used on an Arctic icebreaker is shown in Photograph IV-3. Zinc anodes were installed in a group at the stern of the vessel. Despite the anodes being recessed into the hull, ice removed more than half of them. The anodes were bolted to the hull for easy replacement. On this particular vessel, there were anode banks on both sides of the stern.

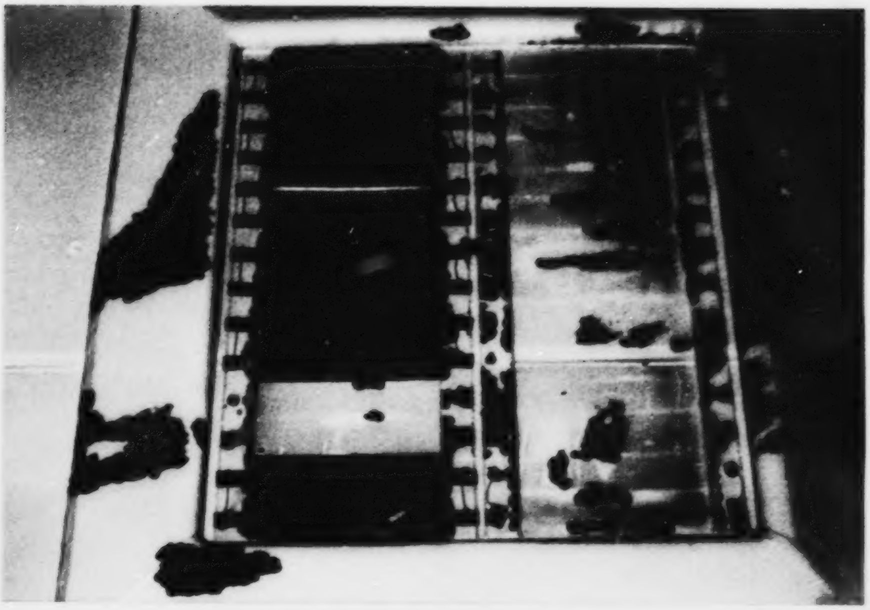
In the majority of the icebreakers that have galvanic anodes on them, the anodes are located at the stern only. Anodes are never installed at the bow or along the ice line because the ice would quickly remove them. Occasionally, the Canadian Coast Guard has used anodes near the keel at midship. This area is less susceptible to ice damage than the bow or ice line, and the anodes will last longer. Zinc anodes have also been used adjacent to the sea inlet boxes. This was done on the C.C G. Des Groseilliers.

3. Effectiveness of Galvanic Anodes

Zinc anodes are more commonly used on ships (including icebreakers) than aluminum anodes. This is primarily because the zinc anodes are more readily available at a lower cost and were introduced to ships well before aluminum anodes.



PHOTOGRAPH IV-2 - GALVANIC ANODES MISSING FROM THE STERN OF ICEBREAKER



PHOTOGRAPH IV-3 - GALVANIC ANODES INSTALLED IN GROUP AT STERN OF ICEBREAKER

Regardless of this, the effectiveness of galvanic anodes on icebreakers is limited compared to ICCP.

Galvanic anodes have a limited current output compared to ICCP Generally, they protect the hull only in the immediate area. Therefore, installing galvanic anodes at the stern will only provide protection to the rudder, propellor, and to the immediate hull only. The anodes will not protect the bow or midships area, particularly if the hull is bare or the protective coating is in poor condition.

Zinc anodes typically have a current output of only 300 milliamperes per lineal meter (100 milliamperes per lineal foot) in seawater if they are flush-mounted. Icebreakers that are now being protected by ICCP systems require at least 150 amperes. To provide the same current using zinc anodes, 460 lineal meters (1,500 lineal feet) of anode material would be needed. Economically, it would not be feasible because of a greater possibility of ice damage to the anodes, an increase in hull resistance in travelling through water or ice, increased fuel consumption, and a life expectancy (if not removed by the ice) of only two years, based on typical anode weights.

To provide complete cathodic protection to an icebreaker, galvanic anodes are not the answer. ICCP should be utilized, based on the success encountered with the Finnish icebreakers.

E. Impressed-Current Cathodic Protection

1. Theory of Operation on Icebreakers

The impressed-current cathodic-protection (ICCP) system used on icebreakers is an automatically controlled system. Figure IV-1 illustrates the basic ICCP insallation on an icebreaker.

The basic system consists of a rectifier, automatic control unit, a pair of zinc reference electrodes, ground (cathodic) connections to the hull and shaft, reference connection to the hull, and two pairs of anodes, complete with appropriate mounting hardware and dielectric shields.

The current from the rectifier unit is controlled by a signal received from the automatic controller. The controller senses the potential measured on the hull to one of the zinc reference electrodes. This signal is then compared to a preset potential, and the current is automatically adjusted to change the hull potential to match this value. For example, if the preset potential to zinc is 200 millivolts and the controller measures 300 millivolts, the current is increased until the potential difference is reduced to 200 millivolts (to a zinc electrode, this infers a greater level of cathodic protection).

2. Basic Equipment

The following information provides general details on the equipment used. Specific details are not available. The information is proprietary, and the companies contacted would only discuss their systems in general terms.

(a) Rectifier

The rectifier is the power unit that converts either single or three-phase A.C. to low-voltage, high-current D.C. power (see Photograph IV-4). A transformer steps down the A.C. voltage, and silicon diodes or selenium stacks rectify the A.C. current to D.C current. A saturated reactor in series with the transformer or thyristors in the primary or secondary circuit controls the current and voltage.

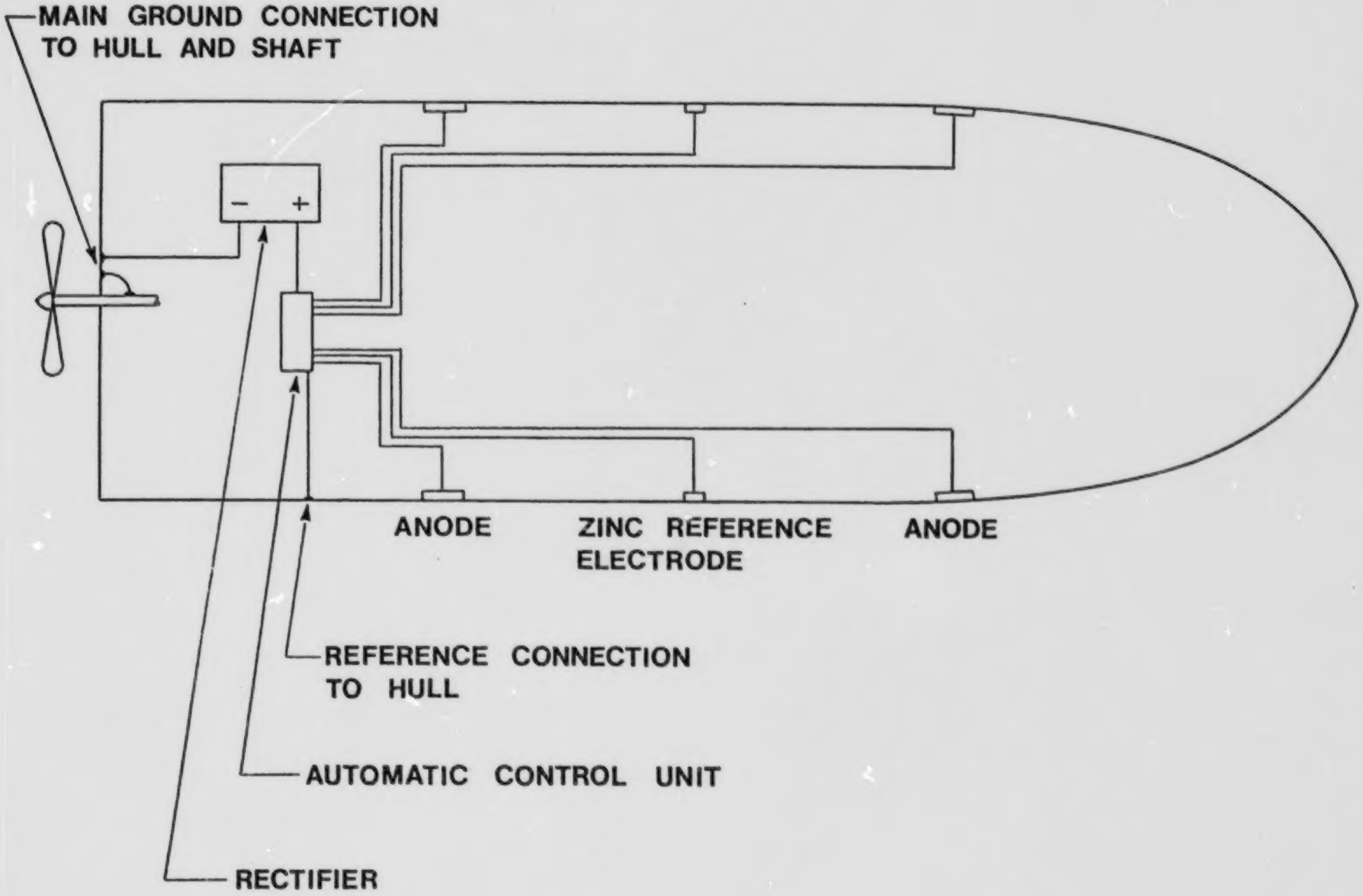
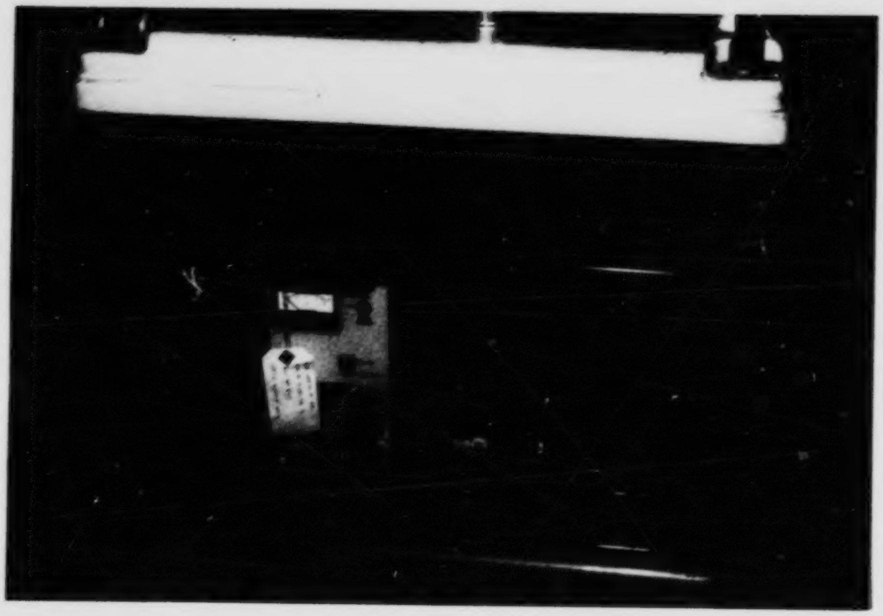

MAIN GROUND CONNECTION TO HULL AND SHAFT
–
+
ANODE
ZINC REFERENCE ELECTRODE
ANODE
REFERENCE CONNECTION TO HULL
AUTOMATIC CONTROL UNIT
RECTIFIER

FIGURE IV-1 - SCHEMATIC OF ICCP SYSTEM ON ICEBREAKER



PHOTOGRAPH IV-4 - RECTIFIER (POWER UNIT) ON FINNISH ICEBREAKER, SISU

Fuses and electronic current limiting are usually included with the rectifier to protect against surges and short circuits.

Most icebreakers require rectifiers rated for 100 amperes to 400 amperes D.C., depending upon the size of the vessel. The operating D.C. voltage is usually less than 30 volts.

For high-current systems, it is often easier to use a number of smaller power untis driven as slaves from a master unit than to have one large rectifier unit. In the event one unit fails, there would still be current available to provide at least partial protection to that area of the hull.

(b) Automatic Controller

The automatic controller may be incorporated into the power unit or it may be separate, as shown in Photograph IV-5. The one shown actually has two control units in it. On the Finnish icebreaker, Sisu, there are two pairs of zinc reference electrodes; one set forward on either side of the hull, and one set aft. The controller can be switched to receive the signal from either or both electrodes in a pair. They also have a manual override feature on them in case the automatic controller malfunctions.

(c) Impressed-Current Anodes

The anodes most commonly used in seawater are a lead/silver alloy, platinized titanium, or platinized niobium.

Photographs IV-6, 7, and 8 show two types of anodes that have been used on icebreakers. The first shows an

PHOTOGRAPH IV-5 - AUTOMATIC CONTROLLER ON ICEBREAKER, SISU oblong-shaped, platinized-niobium anode installed on the Canmar Robert Lemeur. The anodes may also be elliptical in shape. Photographs IV-7 and 8 depict small, circular anodes used on the Finnish icebreaker, Urho. Apparently these were test anodes placed near the bow by Cormet Oy.

The anode material that has been the most successful on the Finnish icebreakers is platinized titanium.

Figures IV-2 and 3 illustrate the method of anode attachment to the hull. These figures represent the general concept. Individual company designs will vary, and they usually are proprietary.

The anodes are mounted on plastic insulation, usually fibreglass, which, in turn, is set into a steel cofferdam that is welded to the hull. As an alternative, a sprayed-on epoxy such as Inerta 160 can be used instead of the fibreglass. Steel bolts are welded to the cofferdam, which fasten the anode and the insulation to the hull. The insulation is also mortared or epoxied to the cofferdam. Epoxy is then applied to the bolts and to the space between the fibreglass and the cofferdam. The bolts are insulated from the anode by plastic sleeves and washers.

A dielectric shield is then applied to the hull adjacent to each anode. It usually consists of a very thick epoxy such as Inerta 160 applied up to 12 mm (0.50 in) thick. The shield extends several meters away from the anodes to improve the current distribution and to minimize the potential gradients.

(d) Zinc Reference Electrodes

The zinc reference electrodes are installed in a manner similar to the anodes. Photograph IV-7 shows a

PHOTOGRAPH IV-6 - PLATINIZED-NIOBIUM ANODE ON CANMAR ROBERT LEMEUR

PHOTOGRAPH IV-7 - IMPRESSED-CURRENT ANODES NEAR BOW OF FINNISH ICEBREAKER, URHO

PHOTOGRAPH IV-8 - IMPRESSED CURRENT ANODES ON ICEBREAKER, URHO

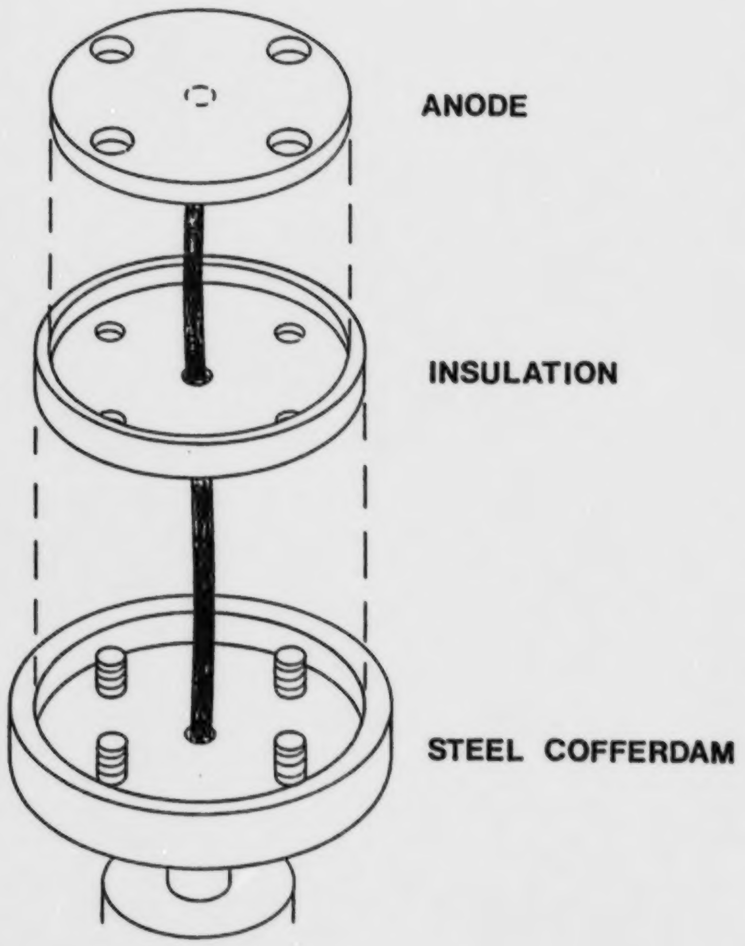

ANODE
INSULATION
STEEL COFFERDAM

FIGURE IV-2 - TYPICAL METHOD OF IMPRESSED CURRENT ANODE INSTALLATION IN HULL

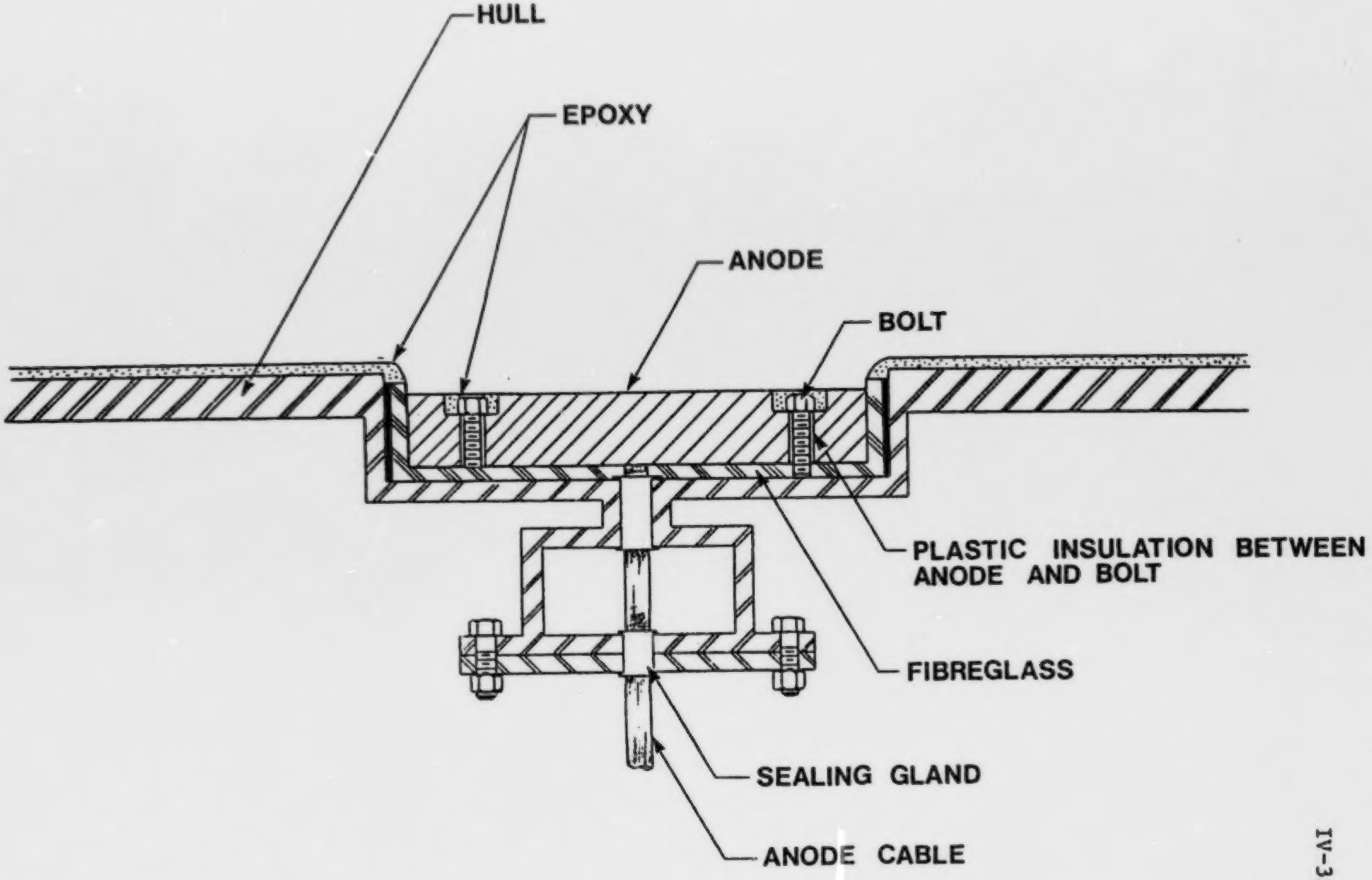

HULL
EPOXY
ANODE
BOLT
PLASTIC INSULATION BETWEEN ANODE AND BOLT
FIBREGLASS
SEALING GLAND
ANODE CABLE

FIGURE IV-3 - GENERAL CONFIGURATION OF IMPRESSED CURRENT ANODE INSTALLATION IN HULL

zinc electrode on the lower portion of the hull of the Urho towards midship.

Zinc electrodes have been found to function best on the Finnish icebreakers. Silver-chloride electrodes have been tried; however, they were not as rugged as the zinc electrodes, and they were susceptible to marine fouling which interfered with the potential readings.

(e) Ground Connection to Ship

Photograph IV-9 shows the typical ground connection to the steel work in the ship and to the shaft. This is typical for all ships with ICCP systems, whether they travel through ice-covered waters or not. It consists of two, split copper rings, one of which is connected to the shaft and rotates with the shaft. This ring is plated with silver, and contact is maintained with the fixed ring by brushes. The fixed ring is, in turn, connected to the hull by an electric cable.

The ground connection on the reference earth for the automatic controller is located remote from the main ground connection for the rectifier. This is done to eliminate feedback which results from significant IR error (voltage drop) near the main ground connection. This could cause instability and improper operation of the ICCP system(47).

3. Anode and Electrode Placement

Anodes are placed away from the areas of severe ice abrasion and impact (the bow and the ice line). On two-anode ships, the anodes are placed at midships well below the ice line on the sides. The anodes are placed as far forward as possible without risking damage to them, since the area of

PHOTOGRAPH IV-9 - GROUND CONNECTION TO SHAFT AND HULL ON ICEBREAKER, SISU greatest current demand is the bow. On four-anode ships (large icebreakers), another pair of anodes are added to the stern.

The positioning of the zinc reference electrodes is particularly critical. If the electrodes are placed near the bow where conditions are most severe, the ICCP will operate at its maximum output in an attempt to protect the bow. This will result in overprotection at the stern and midships. Instead, it is preferable to place the electrodes away from the bow, closer to the anodes, and change the millivolt setting on the automatic controller. This means that the electrode will "see" not only the damaged coating at the bow or ice line, but it will also see the areas of sound coating. In addition, it will respond more quickly to a change in the anode output.

By placing the electrodes in these areas, the bow may not receive complete protection. However, this can be compensated to a certain extent by reducing the millivolt setting on the controller.

4. Protective Current Densities

From the literature reported in the Cook Inlet studies, the minimum current required to protect steel under ice conditions is 430 milliamperes to 650 milliamperes per square meter (40 milliamperes to 60 milliamperes per square foot) of bare steel.

The ICCP log was reviewed for the Canmar Kigoriak for the period of August 1 to 31, 1984 (see Appendix III). During that time, the average current output from the rectifier was 132 amperes. The potential readings on the hull were very good, varying between 34 millivolts and 235 millivolts to zinc. Assuming coating damage of 5% at that time and a current density of 20 milliamperes per square meter on coated steel under ice conditions, the current density on bare steel under ice conditions, the current density on bare steel under ice conditions is 620 milliamperes per square meter (58 milliamperes per square foot). This agrees with the Cook Inlet studies.

Corrintec International uses design figures of 100 milliamperes to 150 milliamperes per square meter (9.3 milliamperes to 14 milliamperes per square foot) for icebreakers under icebreaking conditions. However, this is an overall figure for all surfaces of the vessel, allowing for 20% coating damage. This is equivalent to the Cook Inlet studies, if it is assumed that coated steel requires 20 milliamperes per square meter (2 milliamperes per square foot).

When designing an ICCP system for an icebreaker that has been properly coated with a high-performance coating such as Inerta 160, the following current densities can be used:

- Bare steel under ice conditions: 650 milliamperes per square meter;

- Coated steel under ice conditions: 20 milliamperes per per square meter.

To size the rectifier, 20% coating damage should be allowed for. Therefore, an icebreaker with 2,600 sq m (28,000 sq ft) of hull coated with Inerta 160 would require one or two rectifier units rated for a total of 400 amperes. This agrees quite well with the systems presently being used on the Finnish icebreakers.

If cathodic protection is being considered for a vessel with no coating or a poor one, surface roughness should be taken into account. A severely corroded hull increases the surface area requiring protection. The Cook Inlet studies proved this to be true.

Cormet Oy feels that complete corrosion protection is not possible, particularly in the bow area of the icebreakers. They have had success in attaining potentials to zinc in the 300-millivolt range at the bow. At this potential, Cormet Oy feels corrosion is reduced by approximately 80%.

It should be noted that cathodic-protection current only flows to those areas of the hull in contact with seawater. When ice is in intimate contact with the hull, the ice shields the flow of current from the steel. During icebreaking exercises, this occurs frequently as the hull contacts the ice. It can be readily seen why it is impossible to completely protect the steel with ice continually abrading the steel and removing any polarization films.

F. CASE HISTORIES OF ICCP SYSTEMS

1. Finland

The work performed to date has been on the icebreakers owned and operated by the Finnish Board of Navigation. The two companies involved are Corrintec and Cormet Oy, who perform the engineering design. To date, all equipment, including the anodes, has been manufactured by Corrintec, except the anodes on the new icebreaker, Karhu II. These will be manufactured in Finland.

Platinized-titanium anodes have been found to be the most suitable anode material in ice conditions. The benefits of platinized titanium include a high current density, tensile strength, and hardness. This allows maximum current output from minimum anode material and provides excellent wear resistance to ice. The anode shape is elliptical, except for the new circular one under test on the Urho (see Photographs IV-7 and 8). The small circular anodes would be more resistant to ice damage, but have a higher electrical resistance to seawater than the larger, elliptical ones that are more commonly used. To reduce the electrical resistance, the number of anodes is increased as shown in Photograph IV-8.

The first ICCP system installed was on the icebreaker, Sampo, in 1978 and included the following equipment:

- Rectifier with a capacity of 200 amperes;
- Automatic controller;
- Four platinized-titanium anodes;
- Two zinc reference electrodes.

Based on the success of this system, ICCP was installed on the following icebreakers between 1979 and 1982:

- Varma;
- Voima;
- Tarmo;
- Apu;
- Sisu.

All these vessels are coated with Inerta 160 to provide excellent hull protection.

The Sisu is the largest icebreaker operated by the Board at 16,200 kW (22,300 Bhp). It is protected by two independent ICCP systems; one at the bow and one at the stern. Each system consists of a rectifier rated at 175 amperes, an automatic controller, four platinized-titanium anodes, and two zinc reference electrodes. The systems are far enough apart that they have little influence on each other.

Only three anodes have been lost from ice damage on the icebreakers in six year's service.

The cathodic-protection systems are expected to operate for five years and protect to a maximum of 50% coating loss in that time.

The cost to cathodically protect the Tarmo is shown in Table IV-3. The total is 155,000 mks ($35,500 Canadian), which includes material and labour.

The costs for cathodic-protection installations on most of their vessels were in the order of 100,000 mks (approximately $23,000 Canadian in 1982). The cost of installing an ICCP system on the new icebreaker, Karhu II, will be approximately 400,000 mks ($90,000 Canadian). Apparently, it will have special proprietary anodes installed on it.

The Finnish Board of Navigation stated that the initial costs for application of a high-performance coating and ICCP are approximately six to eight times the cost of a conventional paint system with no cathodic protection. The cost to install the ICCP system and coat with Inerta 160 is 600,000 mks to 800,000 mks ($140,000 to $180,000 Canadian) higher. However, over the life of the icebreaker, it is estimated that the initial high costs will be more than offset by added costs for dry docking, painting new propellors, and weld and hull plating repairs to the vessel with only a conventional paint system. It is estimated that after 29 years, the cost of maintaining the icebreaker with the conventional paint system is in excess of 4 million mks ($1 million Canadian), while the cost to maintain a protected icebreaker is only 1.5 million mks ($340,000 Canadian). These costs do not account for inflation or interest lost on capital expenditures. If these are taken into account (assume a 10% inflation rate and 6% interest on capital), the saving is approximately 11 million mks ($2.5 million Canadian). Fuel savings can also be substantial, as indicated previously in the section on hull coatings.

TABLE IV-3

CATHODIC-PROTECTION COSTS

FINNISH ICEBREAKER

TARMO CLASS(48)

ITEM	1982 COSTS		
	FINNISH MARKS (mks)	APPROXIMATE VALUE IN CANADIAN DOLLARS ($)	VALUE ADJUSTED TO CANADIAN SITUATION ($)
Equipment			
4 Platinized-Titanium Anodes and 2 Zinc Electrodes	20,000	4,500	4,500
Other Equipment (rectifier, cables, automatic controller)	40,000	9 000	9,000
Installation	60,000	14,000*	42,000
Inspection	35,000	8,000	24,000
TOTAL	155,000	35,500	79,500

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*It should be noted that hourly salaries for labour are approximately one third to one half the salaries in Canada; therefore, this figure would be two to three times higher in Canada.

2. Canada

Canmar has two icebreakers equipped with ICCP systems:

- Kigoriak;
- Robert Lemeur.

The system installed on the Kigoriak was Wilson Walton International Aquamatic 750 rated at 31 volts-830 amperes D.C. The power is provided by one rectifier unit.

Ten, 13.6 kg (30 lb) platinized-niobium anodes were installed on the hull with four towards the bow, four at the stern, and two at midships. The anodes are elliptical in shape and approximately 600 mm (24 in) in length.

Inerta 160 was applied as the dielectric shield around the anodes. Within a 3-m (10-ft) radius of each anode, the Inerta 160 varies in thickness from 3 mm to 6 mm (0.125 in to 0.25 in). It was applied by spray and was tapered towards the perimeter.

The anodes were bolted to the hull and sealed with Red Hand Bitumen. Photograph IV-6 shows an anode installed on the Robert Lemeur. The installation on the Kigoriak was similar.

Four zinc reference electrodes were installed in total, two between the bow and midships, and two between the stern and midships on both the starboard and port sides.

The life expectancy of the system is 10 years, although it was reported that mechanical damage from ice had occurred to the anodes after only two years operation.

A data sheet for the ICCP system from the Kigoriak is included as Appendix III. The system averaged 132 amperes for the month of August 1984. The level of protection was set at 150 millivolts to zinc. Reference electrode No. 1 was used as the control electrode. At this current, adequate protection appears to have been attained on the hull of the Kigoriak. The coating damage at the end of 1984 was reported at 5% to 10%.

The system is monitored on a daily basis, and the results are forwarded to the consultant by the chief engineer.

The ICCP system on the icebreaker, Robert Lemeur, differs slightly to that on the Kigoriak. The supplier of the system was Morgan Berkely and Co. (now Corrintec International).

The system's power demand is 19 kW, and the D.C. current rating is 800 amperes. The current is provided through four elliptical, platinized-titanium anodes that are 622 mm by 330 mm (24.5 in by 13 in), as shown in Photograph IV-6. The anodes were embedded with a plastic putty known as Emberoc.

The dielectric shield extends in a 5-m (16.4-ft) radius around each anode and is approximately 1,000 microns (40 mils) thick

Zinc anodes were also used on the Robert Lemeur. Two Canada Metal Z23 anodes were welded inside each bow thruster tunnel. Presumably, this was done to provide localized protection only.

Two zinc reference electrodes were installed in the hull.

The Canadian Coast Guard does not have any icebreakers with ICCP systems on the hull, not including the Cathelco system.

3. United States

The United States Coast Guard did not have any ICCP systems on their icebreakers when they were originally contacted in 1984. They were contemplating the implementation of the systems, based on the success of the ICCP systems on the Finnish icebreakers.

V. SUMMARY OF FINDINGS

A. WELD CORROSION

1. The operating environment of an ice-going vessel promotes increased corrosion of the hull as a whole and preferential attack of weld zones.

2. Preferential weld-zone corrosion can be highly detrimental to the hull strength since it provides a weak link in the overall structure.

3. Weld-zone corrosion can be and has been a problem on Canadian vessels, resulting in increased maintenance costs and in higher operating costs from hull friction.

4. The northern European steel and ship fabrication community believes it has successfully eliminated weld-zone corrosion. Corrosion of weld metal is easily controlled by using more noble weld consumables.

   The elimination of heat-affected zone corrosion requires careful consideration in the design stages. The characteristics which produce a corrosion-resistant HAZ (low manganese content and high welding-heat inputs) give rise to reduced toughness in conventional ship steels. Thus, complete control of HAZ corrosion resistance has required modification of steel chemistry to maintain high toughness.

5. Canadian operators have not yet found HAZ corrosion in itself as a serious problem. Until recently they have used steels with lower manganese contents and unalloyed welding

electrodes, resulting in a weld-zone structure which is not particularly susceptible to localized attack Recent use of high-manganese steels and nickel-alloyed welding electrodes has led to HAZ corrosion. The severity of the HAZ corrosion encountered has not been fully evaluated by this study.

6. No Canadian vessels built to date have addressed control of weld corrosion during actual construction. Welding procedures are usually left to the fabricator, who developes procedures primarily with cost and mechanical requirements in mind. For instance maximum heat-input levels have been specified, while minimum heat inputs are left to the practical limitations of the welding process.

7. The surface condition of the weldment with respect to slag, weld splatter, and weld smoothness can influence the extent of weld corrosion and overall plate corrosion. This is primarily due to increased breakdown of paint films in these areas.

B. COATINGS

The following generalizations summarize the information garnered regarding high-performance coatings for ice-going vessels.

1. The U.S.C.G. study discovered two coatings suitable for icebreaker hulls:

    - International Paints, Inerta 160 epoxy
    - Reliance Universal, Zebron 1864.

    These two products proved to be the best in a series of laboratory and full-scale tests.

The study also investigated the various factors which affect coating performance in ice, including frictional coefficients The findings were as follows.

(a) Coating materials which exhibit low frictional coefficients with little surface damage are best suited as icebreaker coatings.

(b) An optimum hardness exists. Coatings that are softer than ice are easily damaged; whereas extremely hard coatings are chipped and pitted by ice.

(c) Temperature, time in contact, and surface roughness affect the coating's frictional coefficient to ice. Secondary factors include the load (pressure) on the ice and the condition of the ice.

(d) Significant reductions in friction occur by using a smooth corrosion-resistant surface when travelling through ice.

(e) The primary areas of coating wear on the hull are at the bow and the water line (ice line).

(f) Pack-ice presents severer wear conditions to a coating than hard ice.

(g) At low velocities, the coefficient of friction for coatings sliding against ice decreases as the velocity increases. The coefficient is constant at higher velocities.

(h) Ice roughness does not significantly affect the coefficient of friction, except at very low speeds.

(i) The effect of relative humidity on the coefficient of friction is minimal at high velocities. At low velocities, an increase in relative humidity decreases the coefficient.

(j) The frictional coefficient is constant at low pressures, but decreases once the yield strength of the ice is reached.

(k) The coefficient is not affected by the thickness of a hard coating.

(l) Application conditions have a greater effect on the Zebron polyurethane bond strength than on an epoxy such as Inerta 160.

(m) Using Toluene as a cleaner between coats reduced the bond strength of the epoxy. No effect was noted on the polyurethane.

(n) Collodial silica added to an epoxy reduces the hull roughness and increases the wet film thickness that the epoxy can be applied to.

(o) Minimum bond strengths of 103 bar (1,500 psi) are required for an icebreaker coating

(p) Marine fouling is easily removed from low-friction hull coatings, particularly from polyurethane.

(q) Nonsolvented polyurethanes can be used without a filler for corrosion pits.

(r) Application of the coating to only the bow and ice line (20% of the hull) significantly reduces the resistance to travel in ice.

(s) Spraying and squeegeeing a filler coat and applying a top coat is the most effective method for reducing hull roughness.

(t) Zebron polyurethane will cure under less favorable environmental conditions than will Inerta 160 epoxy.

(u) The bond strength of an antifoulant to the Zebron is improved if it is applied while the Zebron is still wet.

(v) High-performance hull coatings significantly reduce the operating and maintenance costs of a ship.

2. In Finland, laboratory and full-scale tests were initiated by Oy Wartsila Ab and the Finnish Coast Guard to study the frictional behavior of ship hulls and ice. An epoxy coating performed well in full-scale testing, which lead to expanded tests on various coatings. Results were similar to the U.S.C.G. study. Inerta 160 emerged from the study as the only coating that withstood full-scale testing.

3. Inerta 160 is a high-solids, two-component epoxy which has gained worldwide use as an icebreaker hull coating. It has successfully been used in Canada, Europe, Finland, Russia, and the United States.

4. Three other coatings have been used as icebreaker hull coatings:

- Zebron polyurethane;
- Hempel Marine Paints Inc. Hempadur 3555 epoxy,
- Devoe Marine Coatings Devran 288 epoxy.

5. Two other coatings have reportedly been used in ice-covered waters. International Paints Intershield EG has been used under light ice conditions, but is not marketed as an ice-breaker coating. Mebon Coatings Bonslip F has reportedly been used on ships travelling in ice; however, there are no case histories available.

6. Surface preparation is the most important factor influencing the life expectancy of a coating system.

7. Adhesion of the coating to the hull is partly determined by surface preparation. Adhesion influences the ability of the coating to withstand abrasion, impact, flexure, marine fouling, cathodic disbondment, and the corrosive environment of oxygenated salt water.

8. Adhesion is divided into three types: chemical, polar, and mechanical. The first two depend on clean steel for reactive sites to form primary and secondary valence bonding. The last type is dependent upon the roughness of the steel.

9. The procedure for cleaning ship hulls in preparation for the application of the high-performance coating is as follows:

   - Water-wash with fresh water at pressures between 140 bar and 690 bar (2,000 psi and 10,000 psi);

   - Remove oil or grease contamination by solvent, alkali, or emulsifier wash;

- Dry-abrasive blast cleaning to remove primer, existing loose paint, rust, scale, and other contaminants using silica sand or a copper-slag grit to at least a near-white finish;

- The surface of the hull must then be vacuumed or blown down with compressed air starting from the top.

10. The minimum anchor pattern or steel profile is 75 microns (3 mils).

11. Blast cleaning is usually performed during the first six hours of an eight-hour shift because coating application requires less time than blast cleaning. It is usually recommended that blast-cleaned steel be coated within eight hours to prevent rust bloom.

12. Sand can be added to the water blast to improve the cleaning action.

13. The pressure-type system is the most efficient method to abrasive blast clean steel because of higher abrasive particle velocities.

14. Silica sand and copper slags are the most commonly used abrasives.

15. New construction is usually cleaned by centrifugal blast cleaning in pieces, primed with shop primer, or coated with the high-performance coating and then assembled in the dry dock. It is more common for the steel pieces to receive the primer.

16. In Finland, the vessels are assembled in large sections then returned to a large paint shop, where the primer is removed by blast cleaning and the high-performance coating is applied.

17. Welds are not normally ground flush on icebreakers. If grinding is performed, it is done only to remove sharp protuberances.

18. Grooved corrosion pits should be cleaned using sand or mineral grits because of the scouring action of these materials as they fragment on impact. High-pressure water blasting also assists the cleaning action.

19. To avoid conflicts of interest, third-party inspection should be used for all cleaning and coating work on icebreakers.

20. High-solids coating materials that are applied as a hot mix should not go on a cold substrate. Poor wetting occurs, resulting in poor adhesion, particularly if the coating is very thick.

21. All the high-performance coatings used on ice-going vessels are self-priming, two-component products, except for Zebron 386-4 which requires a primer.

22. The high-performance coatings are kept at room temperature prior to use, then heated by circulating the material through in-line heaters on the spray equipment.

23. The proper nozzle tip on the spray gun must be used to achieve the correct spray fan and material flow rate.

24. The spray gun should be held 350 mm to 400 mm (14 in to 16 in) from the surface to achieve the proper spray fan for

high-viscosity materials. The spray width should be 250 mm to 400 mm (10 in to 16 in).

25. Prompt solvent cleaning of the spray equipment during shutdowns is essential to the maintenance of the equipment, otherwise the material can quickly set, plugging the hoses.

26. The multipass technique is used to build the required thickness for the high-performance coatings. All are applied in single coats, except for the Devran 288, which is applied in two coats.

27. Welds and other rough areas should be stripe coated just prior to the application of the primary coat.

28. Very rough areas should be filled with coating material by spraying and smoothing the material into the pits using a broad putty knife. Only Inerta 160 has a special filler for this purpose. The other products are used as is.

29. Feathering the edges of existing coating by abrasive blasting provides a smooth boundary between old and new coatings if done properly. This minimizes the chance of ice catching on an edge between the two.

30. Antifouling paints have been used with Inerta 160 on Finnish passenger ferries by applying it six hours after application of the Inerta 160.

31. Graco Hydra-Cat plural-component equipment is commonly used in applying the coatings (except for Devran 288, which uses conventional single-component equipment).

32. The mix ratio of base to catalyst must be frequently monitored to ensure that correct proportioning is maintained.

33. Multiple-coat systems should be avoided. Single-coat application eliminates intercoat delamination. Roughening the first coat by abrasive blasting is not a good substitute for applying a thicker single coat or applying the second coat before the first has cured.

34. The minimum ambient conditions for applying a high-performance coating are as follows:

- A relative humidity less than 85%;

- An ambient temperature greater than 5°C (41°F);

- A steel temperature at least 3°C (5°F) above the dew-point temperature.

Ideally, a temperature of at least 15°C (59°F) for the steel and air is desirable.

35. Oy Wartsila Ab shipyard in Finland uses large paint shops to coat sections of newly constructed ships with Inerta 160. Only welds and damaged areas are coated in dry dock. The shops are used for blast cleaning and painting. They are of sheet-metal construction and are vented and heated by portable heaters.

36. Relative humidity is generally not a problem when painting the ships in Finland; therefore, no control measures are needed.

37. On new construction, Oy Wartsila Ab uses steel-grit abrasive to clean the hulls. The grit is collected and reused.

38. Typical dry-dock shelters consist of tarpaulins and scaffolding or plywood sheeting and angle iron.

39. At very low temperatures such as -40°C (-40°F), it takes 10 million Btu per hour (2,930 kW) for approximately 24 hours to raise the steel temperature at the stern of a large icebreaker to 0°C (32°F). At least another 24 hours are required before the steel temperature approaches 10°C (50°F).

40. Oy Wartsila Ab uses scaffolding that conforms to the shape of the hull for cleaning and coating vessels in dry dock.

41. Most of the high-performance coatings require 4 days to 7 days to develop a complete cure. This means that the ships often enter the water before the coating has cured. In the summer, this is not a problem since water temperatures commonly approach 15°C (59°F) in coastal waters in southern Canada. In the Canadian Arctic, water temperatures are lower, and it is doubtful that the coating would cure.

42. The time expended to hoard a ship is dependent upon the type of shelter, the size of the vessel, and the shipyard experience. On a large icebreaker, 1,000 man-hours or less would be a reasonable labour cost for a plywood shelter. For tarpaulins and scaffolding, the time expended should be less.

43. Cleaning rates of 4.5 sq m (50 sq ft) per man-hour have been reported in Canadian shipyards to achieve a near-white finish.

44. Feathering an existing abrasion-resistant coating such as Inerta 160 is time consuming and requires substantially more abrasive. It has been reported that 0.3 sq m (1 sq ft) of Inerta 160 can be feathered per hour. To remove Inerta 160, five times as much sand is needed than for blast cleaning steel to a near-white finish.

45. The cost to dry dock, clean, and coat a vessel in Canada with Inerta 160 has varied between \$65 and \$161 per sq m (\$6 to \$15 per sq ft) between 1978 and 1982. The costs are dependent upon the size of the ship, the condition of the steel, whether or not a shelter was used, and the experience of the shipyard.

46. For large Arctic-class icebreakers, the 1984 costs approach \$600 per sq m (\$60 per sq ft) if they are dry docked in Vancouver. Once the vessel is in dry dock, the cost to clean additional areas is less. To dry dock in the Arctic, costs can be more than double the cost for similar work in southern Canada. Transportation of materials, equipment, and personnel to site, accommodation of personnel, and construction of shelters are responsible for approximately 30% of the additional costs.

47. The cost to clean and coat vessels in Finland varies from approximately \$34 to \$57 per sq m (\$3.16 to \$5.30 per sq ft). This does not include the construction of shelters.

48. The Canadian Coast Guard icebreakers and other vessels coated with Inerta 160 have performed satisfactorily.

49. The Societe des Traversiers du Quebec operates several ferries using Inerta 160 as the hull coating. The performance of the coating was in question prior to the 1983 dry dockings. The Societe has not provided updated information since the inspections.

50. Two, light to medium icebreakers operated by the Canadian Coast Guard were coated with Devran 288 in 1984. The performance of the coating is not known, since they had not been dry docked.

51. The Canmar Kigoriak was coated with Inerta 160 in 1979. The coating was applied in two test patches, and it performed well. Based on this, the entire hull was coated in 1982. By 1984, it was estimated that the coating had undergone 5% to 10% damage.

52. The shipping company of Oy Henry Nielsen Ab operates five vessels coated with Inerta 160 and is extremely pleased with the performance of the coating.

53. Fuel consumption reductions have been noted on vessels operated by Oy Henry Nielsen Ab and the Finnish Board of Navigation after coating with Inerta 160. The Board notes approximate decreases of 10%. On large passenger ferries, this could amount to cost savings in fuel of $900,000 per year.

54. Teknos Maalit Oy would prefer to see galvanic anodes welded onto the hull of vessels before coating application, rather than damage the coating by welding afterwards.

55. The Finnish Board of Navigation has ten icebreakers coated with Inerta 160 and is very pleased with its performance. Coating damage to several of the icebreakers is less than 15% after two to three seasons. Most of the damage is to the bow and ice-line areas.

56. The Board intends to recoat the hulls of the icebreakers with Inerta 160 every five years, based on the success they have experienced. This is a considerable improvement to the Board. Previously, the hulls were recoated annually. Divers inspect the hulls annually for structural and coating damage.

57. The impressed-current cathodic protection systems have complemented the Inerta 160 coating. No damage to the coating from excessive currents has occurred.

58. The new Finnish icebreaker, Karhu II, presently under construction, has been clad with 316 stainless steel at the ice line. Inerta 160 will be used on the hull elsewhere.

59. Coating the United States Coast Guard Cutter, Northwind, with Inerta 160 reduced fuel consumption by 510,000 litres (135,000 gallons) over a period of one and one-half years. This included icebreaking duties in the Arctic.

60. The U.S.C.G. Cutter Northwind could proceed through ice floes three to six feet thick on only two, 3,000 Bhp engines after coating with Inerta 160. Prior to coating the hull, four 2,000 Bhp engines were needed.

61. Inerta 160 was used to fill welds, rather than rewelding them on the U.S.C.G. Cutter Northwind.

62. International Paints' Intershield EG series has apparently performed well under light, intermittent ice conditions on pulp/paper carriers.

63. Icebreaker coatings and shelters are not frequently used in Great Britain.

64. Mebon Coatings has produced several coatings that may be suitable for service under ice conditions. Bonslip F has reportedly been used on ships travelling in ice. No case histories were available.

C. CATHODIC PROTECTION

The following information summarizes cathodic protection of vessels travelling in ice-covered waters.

1. Cathodic protection is considered to be an essential component of corrosion control on ice-going vessels and should be used in conjunction with a high performance coating to obtain maximum benefit.

2. The original cathodic protection systems for ships in ice-covered waters consisted only of galvanic anodes. Their success depended upon the severity of the ice conditions.

3. The first serious work done on cathodic protection in ice conditions was on the Shell Oil drilling platforms in the Cook Inlet, Alaska, in 1964. Conditions were similar to those experienced on the icebreakers:

    - Low water temperatures;
    - High oxygen content;
    - Rapid currents (high vessel velocity in the case of an icebreaker);
    - Relative movement of ice floes past the steel.

    Because of these conditions, corrosion rates were high and cathodic protection was deemed to be the answer. After ten years of study, various researchers showed that minimum current densities of 430 milliamperes to 650 milliamperes per square metre (40 milliamperes to 60 milliamperes per square foot) were needed for protection. The studies did not, however, locate the anodes where they would be damaged by ice.

4. Corrintec International and Seppo Ylasaari of Cormet Oy achieved the first major breakthrough in ICCP on an icebreaker. In 1978, a system was successfully installed on the icebreaker, Sampo.

5. Galvanic anodes (zinc and aluminum) have been used on ships travelling in ice-covered waters; however, the anodes are susceptible to damage because they are not flushmounted, and they are of limited usefulness because they provide localized protection only.

6. The basic ICCP system consists of a rectifier, automatic control unit, zinc reference electrodes, ground connections, and ICCP anodes.

7. The automatic controller determines the current output from the rectifier by sensing the potential measured on the hull in reference to one of the zinc electrodes. This signal is then compared to a preset potential, and the current is adjusted automatically to change the hull potential to match this value.

8. Most rectifiers on icebreakers are rated to provide 100 to 400 D.C. amperes at less than 30 volts. The current output depends on the size of the vessel.

9. The automatic controller can be set to receive the signal from any one of a number of zinc electrodes on the hull (usually two). The automatic controller usually has a manual override feature on it, in case it malfunctions.

10. The anodes commonly used in seawater are a lead/silver alloy, platinized titanium, or platinized niobium. Platinized titanium has been found to be the anode best suited for use

under ice conditions because of high tensile strength and hardness and the capability to operate at high current densities.

11. Anodes are attached to the hull by proprietary methods, but generally, it involves installing the anodes in a cofferdam which is flush to the hull. The anode is electrically isolated from the cofferdam and is mortared or epoxied and bolted into place.

12. A dielectric shield consisting of the hull coating material is applied to the hull several meters around each anode to improve current distribution and to minimize the potential gradients.

13. Zinc reference electrodes have been found to be superior for use under ice conditions. They are rugged and do not foul.

14. Ground connections to the hull and shaft are standard on all ships with ICCP. Split copper rings are used on the shaft to maintain electrical contact.

15. Anodes are located well below the ice line and usually at midship for two-anode vessels. For four-anode vessels, a second pair is located closer to the stern.

16. The zinc reference electrodes must be located in an area where they will "see" both damaged and sound coating. Placing them too close to the bow causes the rectifier to operate at its maximum output, since this area has the most severe ice conditions and requires the most current. This results in over protection elsewhere.

17. The current densities reported in the Cook Inlet studies appear to agree with the operating data from existing icebreaker ICCP systems. The studies found that a minimum density of 430 milliamperes to 650 milliamperes per square meter is required to form a calcareous deposit.

18. Cormet Oy, corrosion consultants in Finland, feel that attaining potentials in the 300-millivolt range reduces corrosion by 80%.

19. Cathodic protection current only flows to those areas of the hull in contact with seawater. Ice shields the current from the steel.

20. A rough, corroded hull requires more current to cathodically protect it than does a new, smooth hull because the surface area is greater.

21. Cormet Oy and the Finnish Board of Navigation are now testing circular anodes on the icebreaker, Urho. In theory, the circular anodes would be more resistant to ice damage, but a greater number would be required to reduce the anode-to-seawater electrical resistance.

22. Between 1978 and 1982 ICCP systems were successfully installed on six Finnish icebreakers. Only three anodes were lost during a period of six years.

23. The ICCP systems on the Finnish vessels are designed to protect up to 50% coating loss and have a life expectancy of five years.

24. The costs to install cathodic protection systems on Finnish icebreakers in 1982 was typically 100,000 mks ($23,000

Canadian). On the new icebreaker, Karhu II, the cost will be 400,000 mks ($90,000 Canadian) using a proprietary anode system.

25. The Finnish Board of Navigation has calculated that the initial high capital cost of ICCP and a high-performance coating is more than offset over the life of an icebreaker in savings from reduced dry-docking and painting costs, weld and hull plate repairs, and new propellers. Fuel savings also contribute to the long-term operating cost reduction.

26. ICCP systems installed on Canmar's icebreakers, the Kigoriak and the Robert Lemeur, consist of the following.

(a) Kigoriak

- Rectifier rated at 31 volts - 830 amperes D.C.;
- Ten elliptical, platinized-niobium anodes;
- Dielectric shields, 3 m in diameter, 3 mm to 6 mm in thickness, consisting of Inerta 160;
- Four zinc reference electrodes.

(b) Robert Lemeur

- Rectifier rated at 800 amperes D.C.;
- Four elliptical, platinized-titanium anodes, 622 mm by 330 mm;
- Two zinc reference electrodes.

27. The Kigoriak was successfully protected by an average current of 132 amperes during the month of August 1984. The probable coating damage at that time was between 5% and 10%. The level of protection was set at 150 millivolts negative to a zinc reference electrode.

VI. RECOMMENDED PRACTICE

A WELD-ZONE CORROSION

The investigative work and subsequent operational experience by Rautaruukki and ESAB have indicated that both weld and heat-affected zone corrosion can be controlled. Control of HAZ corrosion is expensive, requiring restrictive plate chemistries coordination of efforts between designer and fabricator in the design stages, and continuous monitoring of heat input levels during fabrication. Even after taking these precautions, several instances of HAZ corrosion have been reported by Rautaruukki Oy.

Complete control of HAZ corrosion seems largely to be a question of whether the end justifies the means. Although HAZ corrosion has occurred on newer Canadian vessels, it has not yet become a more severe problem than weld-metal corrosion. This balance between weld and HAZ corrosion may change if corrosion-resistant welding materials are increasingly used. Until that time, there is no need to isolate and attempt to control HAZ corrosion, since corrosion and repairs to weld metal are inevitable. Recommendations in sequence of importance are as follows.

1. More information is needed on the affects of corrosion-resistant weld metals on heat-affected zone corrosion. It is possible that using noble weld metal will greatly increase HAZ corrosion. Since the literature seems to be exhausted on this point, there are two sources of further data:

   (a) Operational experience from the BeauDril icebreakers, the Terry Fox and the Kalvik. Both vessels have hull welds made with 2.5% nickel electrodes;

(b) Laboratory studies using the ESAB corrosion-tank test. Tests should be conducted on higher manganese EH36 plate using 8018-C1 and 7018 electrodes at various heat inputs.

2. Use of alloy welding electrodes should be considered once more data are available concerning the effects of these electrodes on HAZ corrosion.

3. Fabricators should be made aware of the effect of heat input on HAZ corrosion. Referring to data from Relander at al (Figure II-1), an increase in heat input from 2 to 4 kJ/cm $mm^{1/2}$ (14 to 28 kJ/cm for 50 mm plate) at 1.5% manganese content can reduce corrosion penetration by a factor of 2. Maximum heat inputs used in procedure qualification for the "Terry Fox" were 29 kJ/cm. It is possible to weld at these high heat-input levels and maintain excellent HAZ toughness.

   Fabricators should be encouraged to maintain higher levels of heat input during fabrication within the practical limits of the welding process used.

4. The steel company, Rautaruukki Oy, has demonstrated that steels with a lower manganese content can be used to help reduce HAZ corrosion. We would recommend that before the use of this type of steel is considered in Canada, the possibility of reducing HAZ corrosion by using higher welding-heat inputs be investigated. The upper limit of heat input is determined by the limitations of the welding process and the necessity of good Charpy toughness.

   Referring again to the evidence presented by Relander et al (Figure II-1), it is apparent that high heat-input levels have even more effect than manganese content on HAZ corrosion.

Manganese content has the greatest influence at low heat inputs (7 kJ/cm for 50 mm plate), but at high heat inputs (28 kJ/cm), not only is the relative effect reduced, but the overall corrosion rate is much lower.

5. All possible attention should be paid to the cosmetics of finished welds. It has been demonstrated that slag, weld splatter, and irregular weld contour can effect the ability of paint films to adhere. Grinding of welds flush to base metal is not necessary.

B. COATING

1. General

(a) Canadian vessels that will operate in ice-covered waters should be coated with a high-performance coating. The coating that has gained the greatest worldwide use is International Paints Inerta 160, a high-solids, two-component epoxy. The coating has successfully withstood most ice conditions, particularly seasonal ice less than 1 m thick. In severe ice conditions such as those found in the Arctic, coating damage is more extensive. Complete coating loss can be expected in areas of severe ice abrasion and impact (bow and ice line) after several winters service.

(b) Canadian shipyards in conjunction with the Federal Government and the coating manufacturers should cooperate in research and development programs for improving Canadian vessels operating in ice-covered waters. This has been done in Finland to the benefit of all parties involved.

(c) Any coating program should be covered by a contractual agreement which clearly defines the responsibilities of the contractor and the performance expected.

i. The authority of the client and his designated quality control staff/consultant.

ii. An obligation on the contractor to provide proof of his personnel's ability to handle the coatings specified and to clean steel to the required finish.

iii. A description of shelters to be used including monitoring of temperature and relative humidity.

iv. A schedule for cleaning, coating and curing.

(d) Painters should be required to demonstrate their ability to apply the high-performance coating on a test plate prior to actual coating application to the hull. It is not sufficient to have the coating contractor submit references for previous work.

(e) Inspection by an independent agency during surface preparation and coating application is necessary to avoid a conflict of interest by the coating manufacturer. The inspection agency should be appointed by the owner.

2. Surface Preparation

(a) Construct a protective enclosure (shelter) for the vessel. During cold weather (winter months), plywood shelters should be used. The shelters should be heated with portable units and the following conditions maintained:

- Minimum ambient temperature:	15°C (59°F);
- Maximum relative humidity:	80%
- Minimum steel temperature:	15°C (59°F) and at least 3°C (5°F) above the dew-point temperature.

During warm weather in the late spring, summer or early fall, shelters may consist of tarpaulins instead of plywood. Shelters are recommended, regardless of the weather conditions because even in warm weather conditions can be unsuitable for coating application. Storms, wind-blown dust, fog, and cool dry-dock conditions can adversely affect a coating. High humidities frequently are associated with "fine" weather.

(b) Wash the hull using high-pressure water blasting at 690 bar (10,000 psi) water pressure at a flow rate of at least 45 L/m (10 gal/m). This will remove loose coating, salt, oil, and grease. The expected cleaning rate is 42 to 67 sq m/h (450 to 725 sq ft/h). Sand or mineral-slag grit should be injected into the gun to assist in cleaning severely pitted areas of the hull, particularly where the corrosion pits are grooves that undercut the steel.

(c) To assist in the removal of oil and grease, clean rags and brushes dipped in solvent may be used to clean small areas of the hull. On larger areas, water-based acidic or alkaline cleaners should be injected into the water-blasting gun.

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*See Appendix IV

(d) Allow the hull and dry-dock area to dry before commencing dry-abrasive blast cleaning. The relative humidity should be less than the maximum specified by the coating manufacturer.

(e) Areas of the hull that are corroded may be rough and require grinding. Protrusions should be ground flush with the adjacent area.

(f) Dry-abrasive blast clean the hull with silica sand, mineral-slag grit, or a combination of the two using pressurized equipment. Achieve at least a near-white finish as defined by one of the Standards (SSPC, NACE, or Swedish). The profile should be angular, with a height of 75 microns to 100 microns (3 mils to 4 mils). For maximum cleaning production, the nozzle size should be 9.5 mm (3/8 in) and the pressure 7 bar (100 psi).

(g) Where there is existing coating, the edges of the coating should be feathered by abrasive blasting. The entire patch must also be roughened by abrasive blasting to improve adhesion to the following coat. It should be recognized that applying a fresh coating to old coating does not provide an optimum bond. Intercoat delamination could occur despite roughening the old coating.

(h) The steel must be vacuumed or blown off with compressed, clean, dry air starting from the boottop and working down to the keel.

(i) Remove the abrasive material from the dry dock prior to application of the coating.

(j) Complete blasting operations prior to commencing coating application.

(k) All blasting personnel must wear approved safety equipment, including air-fed breathing apparatus. The visors on the helmets should be protected by a disposable plastic film.

(l) Approximately six hours of every eight-hour shift should be allotted for blast cleaning.

(m) To avoid operator fatigue, personnel should take turns abrasive-blast cleaning the hull. When not operating the gun, personnel can ensure that a sufficient quantity of abrasive material is maintained in the pot and move equipment such as the staging and hoses.

(n) On new construction, plate that is centrifugally blast cleaned should be cleaned with steel grit or a mixture of steel grit and shot. Steel shot alone peens the plate and does not provide a suitable anchor pattern. The shop-cleaned plate should be cleaned to a near-white finish.

(o) Abrasive-blast cleaning in the dry dock must remove all conventional paints such as shop primer and loose, high-performance coating. Excessive abrasive material should not remain in the steel profile. Coating adhesion could be adversely affected if all loose material is not removed.

(p) Blast cleaning adjacent to freshly coated steel shall not commence until the coating is in a tack-free condition. Blasting should be initiated approximately 300 mm (12 in) into the coating.

(q) Blasting shall be directed from the coated surface to the adjacent bare-steel surface.

(r) Should the blast-cleaned area exceed the area that can be coated in a working day, the coating should be feathered down to the steel substrate.

(s) Anodes and other equipment that should not be blast cleaned and coated, must be masked. This is particularly important with the platinized surface of the impressed-current anodes.

(t) Complete all internal hull welding prior to coating application to prevent coating damage.

3. Coating Application

(a) Store the coating material at a temperature of approximately 20°C (68°F) several days prior to use.

(b) Check to make certain there is sufficient cleaner in the solvent drum and the pump is ready for operation.

(c) Switch on the heaters for the spray equipment and hoses.

(d) Fill the coating storage containers and ensure no foreign matter will contaminate the material.

(e) Circulate the coating material through the entire spray equipment, including the hoses. The material should be circulated for at least 15 minutes until the material stabilizes at the recommended application temperature.

(f) Check the proportioning ratio by removing the mixing gun, spraying the components in separate containers, and measuring the volume of material.

(g) Switch off the circulation and increase the main pump pressure when spraying is to begin. Ensure the solvent faucet is turned off and the mixing gun is in the spraying position.

(h) As the material is applied, control the wet-film thickness by measuring it with a wet-film gauge. Cross-spray the material to achieve uniform thickness. Ensure the proper tip size is used on the spray gun.

(i) Hold the spray gun 350 mm to 400 mm (14 in to 16 in) away from the surface and apply the material in one application to a minimum thickness of 750 microns (30 mils). Apply the material in multiple passes; once the first coat has gelled, apply successive coats until the desired wet-film thickness is achieved.

Application of a second coat to a cured first coat is not recommended. A chemical bond will not develop, and roughening the first coat only provides a mechanical bond. It is desirable to apply the coating in one application

(j) Monitor the pressure, temperature, and volume of the coating material frequently. If the temperature or pressure changes significantly, stop work immediately and investigate the cause. If the volume of coating material is low and one of the pump sucks air, the mixing ratio will be altered, and work must be stopped immediately.

(k) When the work is interrupted, flush the mixing tube and gun with solvent, reduce the temperature of the material, reduce the main-pump pressure, and switch on the circulation.

(l) When the work is terminated, solvent-flush the mixing tube, hose, and pistol for at least 15 minutes and clean the feeder-pump filters.

(m) In pitted areas of the hull, a filler material should be applied by spraying and spreading the material into the pits. A broad putty knife should be used to spread the material. Apply the topcoat once the filler has gelled.

(n) Cut back and feather the coating in areas where welding will be performed. This is applicable to steel plate that is shop-coated in sections and assembled in the dry dock.

(o) On new construction, hull areas that will rest on keel or bilge blocks should be shop coated with the high-performance coating. The remaining hull area can either be shop coated in sections or coated in the dry dock.

(p) To coat the block areas on old vessels, the vessel must be floated and re-dry-docked after the remaining hull is coated. The coating ajacent to these areas should be feathered. Roughen these areas with abrasive blasting prior to coating the block areas.

(q) The painters must wear protective clothing and breathing apparatus when applying the coating materials.

(r) To develop a full cure, the vessel should remain in the protective enclosure for a given time at a specified temperature. Consult with the coating manufacturer for specific times and temperatures. Premature coating failure could occur if the vessel enters the water too soon.

4. Inspection

The following procedures should be practiced when inspecting the application of high-performance coatings to ice-going vessels' hulls.

(a) Monitor the ambient conditions (air temperature, relative humidity, and dew point) and the steel temperature before starting and at least twice per work shift.

(b) Inspect the equipment of the contractor for safety, including the following:

- Scaffolding for damage and deterioration;

- Scaffolding being plumb and level;

- Handrailing on scaffolding;

- Abrasive-blast equipment including deadman valves, moisture and oil separators, pressure-control valves, electrical grounding, protective clothing and eyewear, filtered and regulated air-supply respirators, and abrasive hoses;

- Couplings on the abrasive hoses should be wired shut;

- Abrasive hose should be stored in a dry place and not curved or bent at a 90° angle;

- Fire hazards such as rags soaked with flammable liquids, use of low flash-point materials, and the presence of ignition sources;

- Adequate ventilation;
- Tight hose connections for spray equipment,
- Weak or worn spots on spray hoses;
- Electrical grounding through hose connections;
- Electrically conductive hose in airless applications;
- Trigger guard on the gun.

(c) Inspect the steel for oil and grease using ultraviolet light. The contamination will fluoresce.

(d) Ensure clean solvent, rags, and brushes are used to degrease the hull.

(e) Inspect the hull for areas which require grinding.

(f) Inspect the quality of the blast-cleaned surface to ensure it meets the requirements of a near-white finish. The visual Standards from either NACE or the Swedish Standards should be used.

(g) Measure the profile of the anchor pattern on the steel using surface-profile tape. Retain the tape for the records.

(h) Inspect the abrasive material used and record product information (manufacturer, product name, type, size, batch number). Use ultraviolet light on the abrasive to ensure it does not contain oil. Sample and retain abrasive for the records.

(i) Inspect coating patches where the existing high-performance coating is to remain on the hull. The coating must be well bonded to the steel, roughened, and the edges feathered.

(j) Inspect the blast-cleaned steel for cleanliness. After the steel has been vacuumed or blown down with compressed air, wipe it with a clean, white cloth. Inspect the steel under 5X power. The steel should not blacken the white cloth, and the profile should not contain rust, excessive abrasive, or previous coating material.

(k) Inspect the dry-dock area to ensure all abrasive material is removed prior to coating application.

(l) Ensure all anodes and other equipment that should not be blast cleaned and coated are masked.

(m) Ensure the coating material is stored at the proper temperature prior to coating application.

(n) Measure the temperature of the coating material prior to and during application.

(o) Check the proportioning ratio of the material at the start and at the end of each work shift. Measure the amount of each component used at the end of the shift.

(p) Monitor the pressure of the pumps to ensure it does not change. Variations could affect the proportioning ratio.

(q) Check the volume of material remaining in the coating containers.

(r) Visually inspect the application to ensure it is smooth and free of drips, runs, and sags.

(s) Sample the coating raw materials and retain for the records. Record information off the containers including manufacturer, product name, product code, date of manufacture, and batch number.

(t) Measure the wet-film thickness to ensure proper thickness is attained during application.

(u) Measure the dry-film thickness as per SSPC Standard PA2; take the average of three readings as the spot measurement and five spot measurements per 9.3 sq m (100 sq ft) of area. The average of the five spot measurements shall not be less than the specified thickness. No single spot measurement shall be less than 80% of the specified thickness.

(v) Holiday test the coating as per NACE Standard RP-02-74 and the coating manufacturer's recommendations. Test welds and rough areas of the hull, as well as smooth plate.

(w) Maintain a photographic log during the work.

(x) Using an adhesion tester that uses steel dollies (such as Elcometer), perform an adhesion test on the coating after it has cured. Set dollies into the hull coating after it has gelled. Place three dollies on the coating in an area of one square meter. Select three areas in total, preferably at the bow, midships, and stern. Cut around each dolly through the coating to the steel substrate, and pull the dollies measuring the adhesive strength.

The average of the three readings in each area should equal the coating manufacturer's test data for the coating.

(y) Record all inspection data in a log book.

C. CATHODIC PROTECTION

1. General

(a) Cathodic protection should be used in conjunction with a high-performance hull coating. Cathodic protection and coatings complement each other.

(b) Impressed-current cathodic protection (ICCP) should be used on all vessels that will be travelling extensively in ice-covered waters. The success of the Finnish ICCP systems on icebreakers proves cathodic protection is effective in reducing corrosion.

(c) The limitations of galvanic anodes must be realized, and their use restricted to specific situations.

(d) ICCP systems should be designed only by competent professionals specializing in cathodic protection with experience on vessels travelling in ice-covered waters.

(e) The hull should be protected to a potential of at least 200 millivolts negative to a zinc reference electrode.

(f) Complete protection may not be possible in areas of severe ice abrasion and impact, such as the bow and ice line. However, studies have shown that a potential of 300 millivolts negative to zinc at the bow will reduce corrosion by approximately 80% even though the hull coating is removed at this area.

(g) ICCP systems should be designed to provide a current density of 650 milliamperes per square meter on bare steel and 20 milliamperes per square meter on steel coated with a high-performance coating. The system should be designed to provide for 20% coating loss.

2. Galvanic Anodes

(a) Galvanic anodes should consist of either zinc or aluminum alloys. Magnesium is not recommended for use in seawater because of its high consumption rate.

(b) Galvanic anodes should be used for localized protection only, such as in areas of bimetallic corrosion or reentrant points.

(c) Galvanic anodes must be used with high-performance hull coatings to be effective.

(d) Fairings are partially effective in providing physical protection to anodes. Their success is dependent upon the severity of ice abrasion.

3. Impressed-Current Cathodic Protection

(a) ICCP systems must be custom-designed for each ship. The designs are proprietary. Generally each system consists of the following.

i. Rectifier

- Quantity: One or two
- Current Rating: 200 amperes to 400 amperes

ii. Anodes

- Platinized metal, usually titanium
- Elliptical in shape
- Recessed into hull in steel cofferdam
- Isolated from hull with fibreglass or epoxy
- Sealed in cofferdam with epoxy
- Quantity: Two or four, on opposite sides of the ship
- Located away from bow, at midship (two-anode ship), and at stern (four-anode ship)

iii. Dielectric Shield:

- Usually consists of extra-thick application of high-performance hull coating (up to 12 mm thick)
- Extends several meters around each anode

iv. Automatic Controller:

- Quantity: One or two
- Set at predetermined potential, usually 200 millivolts negative to a zinc reference electrode
- Can reference one or two zinc electrodes

v. Reference Electrodes:

- Quantity: Two or four
- Manufactured from zinc alloy
- Recessed into hull using same method as anodes
- Usually located on opposite sides of vessel at midship
- Second pair of electrodes can be placed near stern
- Located away from bow

vi. Ground Connections

- One from rectifier to the hull and shafts
- Second connection to the hull from the controller (reference earth)

(b) The anodes should be located away from the bow and below the ice line. The abrasion is most severe in these areas.

(c) The zinc reference electrodes should be placed at midship, away from the bow, toward the anodes. In this location, the electrodes will "see" both sound and damaged coating. The electrodes will be more responsive to current fluctuations, and overprotection will not occur.

(d) The reference earth for the controller must be located remote from the main ground connection. This minimizes the IR error (voltage drop) in the monitoring curcuit.

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APPENDIX I

COATING APPLICATION

REFERENCE LIST

INTERNATIONAL PAINTS

INERTA 160

International Paint Marine Coatings

SHIPS COATED WITH INERTA 160 8.1.1981

Name/Nb. No.	Owner		Year of Coating
SILMÄ	Finnish Coast Guard		1973
ERMAK	Sudoimport (USSR)	trial	1973
MURTAJA	Board of Navigation (Finland)	trial	1973
VARMA	Board of Navigation (Finland)	trial	1974
KARHU	Board of Navigation (Finland)		1975
UISKO	Finnish Coast Guard		1975
SUUNTA	Board of Navigation (Finland)		1975
VUOSAARI	Etelä-Suomen Laiva	trial	1975
JÄÄKOTKA	Port of Kotka		1975
TUIMA	Finnish Navy		1975
TUISKU	Finnish Navy		1975
RYMÄTTYLÄ	Finnish Navy		1975
MERI-PEKKA	Vesi-Pekka Oy		1975
FINNJET	Oy Finnlines Ltd.		1976
LUNNI	Neste Oy		1976
TERVI	Neste Oy		1976
TYRSKY	Finnish Navy		1976
ARCTIC WASA	Salenrederierna (Sweden)	trial	1976
SISU	Board of Navigation (Finland)		1976
KARJALA	Finnish Navy		1976
OJIBWA	U.S. Coast Guard (USA)		1976
KONE	Kone Oy		1976
POLARIS	Rieber's Rederi (Norway)	trial	1976
SOTKA	Neste Oy		1976
TUULI	Finnish Navy		1976
KALLA	Board of Navigation (Finland)		1976
GLACIER	U.S. Coast Guard (USA)		1977
KAPITAN CHECHKIN	Sudoimport (USSR)		1977
PORIN KARHU	Port of Pori		1977
ALE	Board of Navigation (Sweden)		1977
ABEGWEIT	C.N. Marine (Canada)		1977
JOHN HAMILTON GRAY	C.N. Marine (Canada)		1977

Name/Nb. No.	Owner		Year of Coating
TEBOSTAR	Suomen Petrooli Oy		1977
TIIRA	Neste Oy		1977
ESSO NORDICA	Esso Oy		1977
TUPPER	Transport Canada (Canada)		1977
SIR WILLIAM ALEXANDER	Transport Canada (Canada)		1977
EJDERN	Alands Landskapsstyrelse (Finland)		1977
ISO-PUKKI	Port of Turku		1977
PASILA	Etelä-Suomen Laiva Oy	trial	1977
LEVATOR	Kone Oy		1977
KAPITAN PLAHIN	Sudoimport (USSR)		1977
TEUVO	Port of Helsinki		1977
BALTIC WASA	Salenrederierna (Sweden)		1977
JÄÄSALO	Port of Kemi		1977
PELLINKI	Finnish Navy		1977
LOUHI	Finnish Navy		1977
KAPITAN CHADAEV	Sudoimport (USSR)		1977
UIKKU	Neste Oy		1977
LOUIS SAINT-LAURENT	Transport Canada (Canada)		1978
GOTHIC WASA	Salenrederierna (Sweden)		1978
KAPITAN KRUTOV	Sudoimport (USSR)		1978
KAPITAN BUKAEV	Sudoimport (USSR)		1978
KAPITAN ZARUBIN	Sudoimport (USSR)		1978
SONG OF NORWAY	Royal Caribbean Cruise Line (Norway)	trial	1978
YMER	Board of Navigation (Sweden)		1978
POSEIDON	Neptun Oy		1978
ESSO SAIMAA	Esso Oy		1978
HEIMDAL	City of Stockholm (Sweden)		1978
TARMO	Board of Navigation (Finland)		1978
INZHENER MACHULSKIY	Sudoimport (USSR)		1978
FREDERICK CARTER	C.N. Marine (Canada)		1978
FUJI	Japanise onwer (Japan)		1978
STROPTIVYJ	Sudoimport (USSR)		1979
SPRAVEDLIVYJ	Sudoimport (USSR)		1979

Name/Nb. No.	Owner		Year of Coating
FREJ	Board of Navigation (Sweden)		1979
STAR	U.S. Coast Guard (USA)		1979
STAHANOVEZ	Sudoimport (USSR)		1979
SUVOROVEZ	Sudoimport (USSR)		1979
NJORD	Board of Navigation (Sweden)		1979
ODIN	Board of Navigation (Sweden)		1979
CAMILLE MARCOUX	Taversiers du Quebec (Canada)		1979
IMPERIAL BEOLFORD	Imperial Oil (Canada)		1979
VOIMA	Board of Navigation (Finland)		1979
SAMPO	Board of Navigation (Finland)		1979
SIBIRSKIJ	Sudoimport (USSR)		1979
VARMA	Board of Navigation (Finland)		1979
CANMAR KIGORIAK	Dome Petroleum (Canada)	trial	1979
LABRADOR	Transport Canada (Canada)		1979
WASA EXPRESS	Oy Vaasa-Umeå Ab		1979
CHIMO	Newfoundland Steamships (Canada)	trial	1979
BOTNIA EXPRESS	Oy Vaasa-Umeå Ab		1979
BEAUPORT	Transport Canada (Canada)		1979
CABOT	Newfoundland Steamships (Canada)	trial	1979
IMPERIAL ACADIA	Imperial Oil (Canada)		1979
EUROPA 2	Enso-Gutzeit Oy		1979
RIJNBORG	Wagenborg B/W (Netherlands)		1979
REPLOT 2	TVH (Finland)		1979
TURSO	Hangon Hinaus Oy		1979
MONTCALM	Transport Canada (Canada)		1979
TEBO OLYMPIA	Suomen Petrooli Oy		1979
VIKING SAGA	Rederi Ab Sally		1979
VIKING SONG	Rederi Ab Sally		1979
KONTULA	Etelä-Suomen Laiva Oy		1979
GUDINGEN	Alands Landskapsstyrelse		1979
SEILI	Board of Navigation (Finland)		1979
POLAR STAR	U.S. Coast Guard (USA)		1979
POLAR SEA	U.S. Coast Guard (USA)		1979
CHEVRON COLORADO	Chevron Shipping (USA)		1979

Name/Nb. No.	Owner	Year of Coating
UNCLE LOUIE	Castagnola (USA)	1979
ANTONINA C	Castagnola (USA)	1979
GINA KAREN	Ronani (USA)	1979
WILLA G	Cutri Median (USA)	1979
ISLAND PRINCESS	Van Kamp (USA)	1979
JOLENE	Joe Giodarni (USA)	1979
CORNUCOPIA	Union Oil (USA)	1979
KEMIRA	Oy Finnlines Ltd.	1980
KAPITAN DRANITSKIJ	Sudoimport (USSR)	1980
LETTO	Board of Navigation (Finland)	1980
VIAPORI	Å Österlund	1980
SUOMENLINNAN LAUTTA	City of Helsinki	1980
APU	Board of Navigation (Finland)	1980
VIKING 5	Rederi Ab Sally	1980
VIKING 1	Rederi Ab Sally	1980
TEBONIA	Suomen Petrooli Oy	1980
KÖKAR	Ålands Landskapsstyrelse	1980
KUMLINGE	Board of Navigation (Finland)	1980
Under Construction:		
RR 15 Drillship	Rauma-Repola Oy	1980-1981
Nb. 306	Valmet Oy Vuosaari Helsinki	1980-1981
Nb. 430	Wärtsilä Oy Helsinki	1980

In addition about 120 trawlers, tugs and small vessels for various owners in Finland and 4 small tugs in USA.

RELIANCE UNIVERSAL

ZEBRON

CASE HISTORY LIST
OF
ZEBRON (tm) APPLICATIONS
TO
MARINE VESSELS

April 1984

Zebron is the registered trademark of Zebra, S.A. and refers to the Canadian manufactured formulation which is marketed in the U.S.A. under the tradename, Torbron.

ZEBRON APPLICATIONS TO MARINE STRUCTURES

CLIENT	SERVICE LOCATION	STRUCTURE	SPECIFICATION	DATE COATED	SERVICE	LATEST REPORT
B.C. Ferry Corp.	(a) Tsawwassen	(a) Dock support pontoons	- 0.5 mm coating for corrosion protection.	1980	4 years	1981 - coating in good condition.
	(b) Bear Cove	(b) Dock support pontoons	- 0.5 mm coating for corrosion protection.	1980	4 years	1981 - coating in good condition.
	(c) Prince Rupert	(c) Pontoons. Non-skid walkways.	- 1 mm for non-skid areas	1980	4 years	1981 - coating in good condition.
Burrard Dry Dock	Vancouver, B.C.	Exterior coating of pilings on new dry dock for long-term corrosion protection	- 0.5 mm coating to H-piles. 1 mm at welds	1980	4 years	1981 - coating in good condition.
B.C. Ferry Corp. (new docks)	(a) Departure Bay (b) Swartz Bay (c) Tsawwassen	Structural steel pilings and supports for new car ramp	- 0.5 mm for corrosion protection	1981	3 years	1981 - coating in good condition in all locations. 1982 - coating in good condition at Swartz Bay & Tsawwassen; some peeling reported at Departure Bay - to be investigated.
United States						
State of Alaska City of Dillingham	Dillingham, Alaska	Container Dock	- 0.75 mm to steel pipe piles	April 1982	2 years	May 1983 - coating standing up well to ice abrasion.
State of Alaska Cordova Bay	Cordova Bay, Alaska	Cordova Bay Terminal	- 1.5 mm to steel pipe piles	Sept. 1982	1-1/2 years	Not available.
State of Alaska	City of Ketchikan	Ketchikan Marine Terminal	- 0.625 mm to 80 ft sheet piling at tidal and splash zones (10,000 sq ft)	Spring 1983	1 year	Not available.

ZEBRON APPLICATIONS TO MARINE STRUCTURES

CLIENT	SERVICE LOCATION	STRUCTURE	SPECIFICATION	DATE COATED	SERVICE	LATEST REPORT
U.S. Coast Guard	Coast Guard Base Long Beach, CA	Steel piles	- 1 mm Zebron coating to steel piles	1972	11 years	1978 - Coating in excellent condition except for those areas under constant abrasion from steel rings.
			Europe			
Elf Norge	Norwegian Sector North Sea	Stainless Steel Water Rejection Shaft	- 1 mm Zebron coating to shaft	1981	3 years	No problems reported to date.
			COAL APPLICATIONS			
National Harbours	Prince Rupert, British Columbia	Ridley Island Coal Terminal	- 0.5 mm to marine pipe piles	Summer 1982 Spring 1983	2 years	Not available.
			United Kingdom			
British Steel Corporation	United Kingdom	Coal Feed Bunkers supplying crushers	- 4.0 mm Zebron coating over P-222 primer - Zebron applied to reduce "hang-up" of wet coal. Size 12 mm 8% - 10% H_2) Flow rate: 300 tons/hour	1980	4 years	No problems reported to date.

ZEBRON APPLICATIONS TO MARINE VESSELS

CLIENT	SERVICE LOCATION	VESSEL	SPECIFICATION	DATE COATED	SERVICE	LATEST REPORT
B.C. Department of Highways	Pacific Coast	Tug "MV Kulleet"	- non-skid deck coating - 1.0 mm Zebron coating to the exterior hull to reduce skin friction - antifoul Interswift applied after 12 hrs to roughened Zebron surface after recoat	1980	4 years	Fuel savings for 1st year of 5%. Average increase in speed of 10%. 1984 - ship recoated to 0.625 mm with no primer (initial application was undermilled).
B.C. Department of Highways	Pacific Coast Ferry	"Quadra Queen"	- interior coating of sewage tanks and valves	1981	2 years	Not available.
Burnaby Tugboat Ltd.	Pacific Coast	Tug "MV Rasp"	- exterior hull coating and non-skid deck coating	1981	2 years	Not available.
Canadian Coast Guard	Western Region	CCG Icebreaker "Wolf"	- exterior coating to bow	1976	8 years	1982 - coating in excellent condition. No significant loss apparent.
Canadian Coast Guard	Newfoundland Region	CCG Icebreaker "Sir Humphrey Gilbert"	- exterior hull coating	1980	4 years	1981 - coating in good condition. No loss attributed to coating performance. 1982 - some loss to ice-line. Bottom coating in excellent condition.
Canadian Coast Guard	Laurentian Region	CCG "R" Class Icebreaker "Des Groseilliers"	- exterior hull coating 1 mm thickness	1982	2 years	Coating in excellent condition.

ZEBRON APPLICATIONS TO MARINE VESSELS

CLIENT	SERVICE LOCATION	VESSEL	SPECIFICATION	DATE COATED	SERVICE	LATEST REPORT
Gulf Canada Resources Inc.	Beaufort Sea N.W.T.	Conical Drilling Rig "Kulluk"	- coating of ice shields to 2.5 mm - coating of underwater hull and moon pools to 1.0 mm thickness	1982-1983	1 year	Not available.
Gulf Canada Resources	Beaufort Sea N.W.T.	Mobile Arctic Caisson "Molikpaq" (MAC)	- coating of ice shields to 1.5 mm thickness	1982-1983	6 months	Not available.
Nanaimo Harbours Board	Nanaimo, B.C.	Patrol Boat II	- 0.75 mm to 2.5 mm to underwater aluminum hull	January 1982	2 years	Not available.
Rivtow Straits Ltd.	Pacific Coast	Tug "Rivtow Viking"	- 1 mm coating to kort nozzle - exterior hull coating	1980	3-1/2 years	1981 - coating in excellent condition
Seaspan International Ltd.	Pacific Coast	Coast Tugs: "Commander" "Mariner" "King" "Victor" "Voyager" "Sovereign"	- non-skid deck coating - corrosion coating to bulwarks	1981	3 years	Coating on all vessels in excellent condition.
Seabus Harbour Ferry	Vancouver Harbour	"Beaver"	- exterior coating to aluminum pontoons	1981	2 years	1982 - coating in excellent condition
Upper Lakes Shipping Company ltd.	Atlantic Coast	"Canadian Pioneer"	- 1 mm coating to underwater hull for ice service - 2 mm coating to bow thruster tunnels - 0.5 mm coating to unloading boom for corrosion protection	1982	2-1/2 years	June 1983 - coating in excellent condition.

ZEBRON APPLICATIONS TO MARINE VESSELS

CLIENT	SERVICE LOCATION	VESSEL	SPECIFICATION	DATE COATED	SERVICE	LATEST REPORT
			United States			
Bludworth Shipyards Houston, Texas	Gulf of Mexico	"OSV Orion"	- exterior hull coating to decrease fuel consumption	1978	6 years	No report.
Foss Launch & Tug	North Pacific	"Alaska Husky"	- exterior coating to underwater hull	1976	8 years	1980 - 10% coating repair.
Totem Ocean Trailer Express	Pacific Coast to Alaska	"Westward Venture"	- 1 mm Zebron to iceline	1982	2 years	Excellent condition.
Totem Ocean Trailer Express	Pacific Coast to Alaska	"MV Greatland"	- 1 mm Zebron to iceline	1983	1 year	Excellent condition.
U.S. Coast Guard	Great Lakes	U.S. Coast Guard Icebreaker "Mackinaw"	- exterior coating to underwater hull	1975	9 years	1978 - no coating repair.
U.S. Coast Guard	Great Lakes	U.S. Coast Guard Icebreaking Tug "Raritan"	- exterior coating to underwater hull	1974	10 years	1976 - coating in excellent condition - less than 5% repair. 1981 - dry dock interval 4 yrs. Iceline coating repaired, bottom coating in excellent condition.
U.S. Coast Guard	Atlantic Region	U.S. Coast Guard Cutter "Munro"	- high build coating, 1.5 mm Zebron applied directly to blasted surface - antifoul top coat Duvoe ABC applied directly to cured Zebron coating.	1983	1 year	1984 - coating in excellent condition

ZEBRON APPLICATIONS TO MARINE VESSELS

CLIENT	SERVICE LOCATION	VESSEL	SPECIFICATION	DATE COATED	SERVICE	LATEST REPORT
			United States			
U.S. Coast Guard	Great Lakes	U.S. Coast Guard Icebreaker "Glacier"	- exterior coating to underwater hull (port side) - Inerta 160 on starboard side	1977	7 years	1978 - extensive coat-repair to both Zebron and Inerta. Zebron - 60% removed at iceline. Inerta iceline loss and extensive spot corrosion over entire area coated.
U.S. Coast Guard	Atlantic Region	U.S. Coast Guard Cutter "Dallas"	- high build coating 2.5 mm Zebron to rudders	1978	6 years	1979 - no coating damage. 1982 - Zebron U.M. Mastic repairs to 10% of area. Antifoul top coat - 2 coat polyamide epoxy no. 156 applied directly to roughened Zebron to meet U.S. Govt. mil spec P-24441. 1984 - Zebron U.M. repairs to additional 10% of area. Antifoul top coats applied as above.
			United Kingdom & Europe			
Chevron Petroleum	Ninian Field North Sea	Offshore Platforms in Ninian Southern, Northern and Central Fields	- 1.0 mm Zebron non-skid deck coating with RR Primer	1980 1981 1982	3-4 years	Not available.
Fred Olsen Line	North Sea	"Sea Brute"	- 2 mm coating to propellor shaft casings	1975	9 years	1979 - coating in excellent condition.

ZEBRON APPLICATIONS TO MARINE VESSELS

CLIENT	SERVICE LOCATION	VESSEL	SPECIFICATION	DATE COATED	SERVICE	LATEST REPORT
			United Kingdom & Europe			
Occidental Petroleum		"MSV Tharos"	- 750 microns to diving bell curser and cimbals for bell recovery	1979	5 years	No problems reported to date.
Occidental Petroleum		"Piper"	- 1 mm to strengthening leg clamp	1979	5 years	No problems reported to date.
Oceaneering		Norwegian Sector	- 5 mm to diving habitat as a protective coating and thermal insulation.	1979	5 years	No problems reported to date.
Royal Norwegian Navy	North Sea	Gate Vessel Navy Tug VSD 13	- exterior hull coating	1980	4 years	Not available.
Shell Oil	North Sea	Offshore Platform Fenders	- 1 mm Zebron coating with RR Primer	1981	3 years	1982 - Coating is in excellent condition.

HEMPEL'S MARINE COATINGS

HEMPADUR 3555

REFERENCE LIST HEMPADUR 3555

AME OF VESSEL	OWNER/MANAGERS	DATE OF APPL.	GRT/YEAR BUILT	AREA TREATED
DRIAN MAERSK	A.P. Moller, Denmark	01/82	29,901/1975	Rudder/stabilizers/ bow thruster
LBERT MAERSK	Do.	02/82	29,901/1975	Do.
NDERS MAERSK	Do.	06/82 10/83	29,901/1975	Do. Repair of do.
NNA MAERSK	Do.	01/82 01/84	29,901/1975	Do. Repair of do.
RCTURUS	EFFOA, Finland	10/82	8,425/1982	Ramps/driving areas
RNOLD MAERSK	A.P. Moller, Denmark	07/84	30,468/1975	Rudder/stabilizers/ bow thruster
RTHUR MAERSK	Do.	01/82	29,568/1975	Do.
RVEPRINS KNUD	D.S.B., Denmark	06/84	4,836/1963	Flat bottom/vertical sides
URORA	EFFOA, Finland	07/81	8,854/1971	Rudder
EL MAERSK	A.P. Moller, Denmark	04/84	29,903/1976	Rudder/stabilizers/ bow thruster
LTIC EAGLE	United Baltic Corp., U.K.	08/83	6,376/1979	bow area (480 m^2)
RGITTA	Elbe Transport Union, W. Germany	09/83	997/1976	Vertical sides (700m^2)
RE QUEEN	OY Bore Line AB, Finland	08/81	6,850/1980	Bottom/belt area
NADIAN EXPLORER	Furness Withy Shipping, U.K.	01/81	26,051/19--	Stb. midships (test 2 m2)

REFERENCE LIST HEMPADUR 3555

NAME OF VESSEL	OWNER/MANAGERS	DATE OF APPL.	GRT/YEAR BUILT	AREA TESTED
CAPITAINE PLEVEN II	COMAPECHE, France	09/84	2,435/1973	bottom, fore 890 m^2
CHAUMONT	Ste Maritime des Petroles B.P., France	12/81	131,654/1976	Bow area
EMDEN Ex. DOMIN EMDEN	Transerz, W. Germany	08/81	3,999/1980	Bulbous bow
ESSO DEMETIA	Esso Tanker, London, U.K.	02/81	125,293/1973	Bow area
ESSO FAWLEY	Do.	12/83	11,046/1966	Topsides
EXXON PRODUCTION PLATFORM	Exxon, U.S.A.	08/83	Platform	Deck 150 m^2 (test)
GUELO Ex. VIKING 6	Rederiaktiebolaget Sally, Sweden	10/76	5,149/-	Bow area
GULF GATINEAU	Gulf Oil Canada Ltd., Canada	10/83	DWT 8,900/1975	Do.
GULF MACKENZIE	Do.	07/84	5,924/1977	Do.
GUTE	Rederi AB Gotland, Sweden	08/83	1,800/1979	vertical sides, boot
INZHENIER BASHKIROW	Baltic Shipping, Leningrad	04/84	4,009/1975	Bulbous bow
INZHENIER MACHULSKIY	Do.	06/84	4,008/73	Do.
KONTULA	Etala-Suomen Laiva, Finland	06/80	19,918/1980	Vertical side, port, (1000 m2)

REFERENCE LIST HEMPADUR 3555

NAME OF VESSEL	OWNER/MANAGERS	DATE OF APPL.	GRT/YEAR BUILT	AREA TREATED
LAURA MAERSK	A.P. Moller, Denmark	02/83	36,000/1980	Rudder/stabilizers
LOVISA GORTHON	Gorthon Lines, Sweden	07/83	4,094/1979	Vertical sides, stb. port (90 m^2)
		07/84		Repair of 140 m^2
MAGRITTE	C.M.B., Belgium	10/83	38,235/1983	Cargo hold 4 (1,850m^2
MAJGARD	Rederibolaget Garden, Mariehamn	04/84	1,536/1974	Vertical bottom
MARGIT RYE	R.G. Nielsen, Denmark	08/83	245/1965	Topsides (250 m^2)
MARGO	Zanen Verstoep, Netherlands	08/83	Fast boat/1983	Rudder (test)
MINERAL ANTWERPEN	C.M.B,, Belgium	10/83	75,728/1981	Cargo hold No 5 and hopper sides
MONTLOUIS	Compagnie Atlantique Maritime, France	07/82	4,210/1977	Port side, forward
MYRSINIDI	Fafalios Ltd,. U.K.	07/82	5,511/1977	Bulbous bow stb. side
NANOK S.	A.E. Sorensen, Denmark	06/84	2,208/1962	Bow area, 175 m^2
NICHOLAYEV	Sovbunker, Moscow, USSR	11/83		
NORDSEE	W.S.V., Hamburg, W. Germany	06/80 06/81 08/82	8,785/1978	Hopperroom
NORDSTRAND	Arne Jensen, Denmark	08/83	149/1973	Topsides (300 m^2)

REFERENCE LIST HEMPADUR 3555

AME OF VESSEL	OWNER/MANAGERS	DATE OF APPL.	GRT/YEAR BUILT	AREA TREATED
OLLUX	EFFOA, Finland	05/81	8,687/1977	Bow area
ONCE	Puerto Rico Marine Management, USA	06/83	17,513/-	Rudder
ANTANIA	ITC Haarlem, Netherlands	09/82	899/1977	2 kort nozzles
AUDI GLORY	Interocean Shipping, U.K.	11/81	122,296/1974	bulbous bow/ frame 70-72 + 90
IRIUS	EFFOA, Finland	07/82	4,470/1973	stern ramps
TAR DOVER	Norwegian Owner	06/83	23,839/1977	Hold No 1 (1500m^2)
TIG GORTHON	Gorthon Lines, Sweden	07/83	4,095/1979	Vertical side (1m^2) Test
		08/84		180 m^2 welding seams
VENDBORG	A.E. Sorensen, Denmark	4/84	1,594/1967	Bow area (120m^2)
EXACO WINDSOR	Texaco Overseas Tankship Ltd., U.K.	05/84	54,110/1980	Fender areas (360m^2)
ORVANGER	Westfal-Larsen & Co., Norway	06/83	17,056/1976	Bow area 150m^2
IKING SALLY	Rederiaktiebolaget Sally, Sweden	04/80	15,566/1980	Vertical sides + boottop
IKING 4	Rederiaktiebolaget Sally, Sweden	05/77	4,477/1973	Rudder
ast Bay No. 3	Shell Offshore Inc., U.S.A.	07/84	Rig	Water line, boat landings
outh Pass 62B	Do.	07/84	Rig	Water line + part of legs

INTERNATIONAL PAINTS

INTERSHIELD EG SERIES

INTERSHIELD EG SERIES EXPERIENCE LIST
(FULL VESSELS AND APPLICATIONS GREATER THAN 200 SQ.M.)

VESSEL NAME	SHIPOWNER	COUNTRY	VESSEL TYPE	DWT	CAUSE OF DAMAGE	DATE OF APPLICATION	VESSEL AREA	AREA COATED
"BRANSFIELD"	BRIT. ANTARTIC SURVEY	UK	RESEARCH SURVEY	3,500	ICE	JULY '80	UNDERWATER	1,600 sq.m.
"HUMBER ARM"	BERGESEN	NORWAY	CARGO	7,200	ICE	JULY '80	BOW/FLATS	600 sq.m.
"JOHN BISCOE"	BRIT. ANTARTIC SURVEY	UK	RESEARCH SURVEY	1,000	ICE	AUG '80	UNDERWATER	1,500 sq.m.
"MOBIL FALCON"	MOBIL	UK	TANKER	277,000	FENDERS	DEC '80	TOPSIDES/ BOOTTOP	700 sq.m.
"GREENGARTH"	CORY SHIP TOWAGE	UK	TUG	140	FENDERS	FEB '81	TOPSIDES	100 sq.m.
"BARGARTH"	CORY SHIP TOWAGE	UK	TUG	140	FENDERS	APR '81	TOPSIDES	100 sq.m.
"DANEGARTH"	CORY SHIP TOWAGE	UK	TUG	140	FENDERS	JUNE '81	TOPSIDES	100 sq.m.
"BOTAFOGO"	ALIANCA	BRAZIL	CARGO	12,400	ICE AND FENDERS	JUNE '81	UNDERWATER	4,500 sq.m.
"LONDON TRADER"	MARATHON SHIPPING	UK	ULCC	362,000	FENDERS	JULY '81	SIDES	1,000 sq.m.
"ENTALINA"	SHELL TANKERS	UK	TANKER	31,000	FENDERS	JULY '81	BOOTTOP	2,000 sq.m.
"BUTEGARTH"	CORY SHIP TOWAGE	UK	TUG	140	FENDERS	AUG '81	TOPSIDES	100 sq.m.
"VENTURE CANADA"	CONOCO	UK	VLCC	247,000	FENDERS	SEPT '81	BOOTTOP	900 sq.m.
"CORNERBROOK"	BERGESEN	NORWAY	CARGO	7,200	ICE	SEPT '81	BOW	800 sq.m.
"TRANSVAAL"	D.A.L.	GERMANY	CONTAINER	50,000	FENDERS	SEPT '81	BOOTTOP U/W AREA SIDES	1,150 sq.m. 750 sq.m.
"ESSO MADRID"	EXXON	USA	VLCC	388,000	FENDERS	SEPT '81	SIDES	1,300 sq.m.
"PLUMGARTH"	CORY SHIP TOWAGE	UK	TUG	140	FENDERS	NOV '81	TOPSIDES	100 sq.m.

VESSEL NAME	SHIPOWNER	COUNTRY	VESSEL TYPE	DWT	CAUSE OF DAMAGE	DATE OF APPLICATION	VESSEL AREA	AREA COATED
"ESSO HUMBER"	ESSO	UK	TANKER	21,500	ICE AND FENDERS	NOV '81	UNDERWATER	1,500 sq.m.
"CATHERINE L"	CERES HELLENIC	GREECE	BULKER	27,300	FENDERS	NOV '81	BOW	425 sq.m.
"HOLMGARTH"	CORY SHIP TOWAGE	UK	TUG	140	FENDERS	NOV '81	TOPSIDES	100 sq.m.
"PARANAGUA"	E.A.C.	DENMARK	TANKER	33,000	FENDERS	NOV '81	TOPSIDES	2,100 sq.m.
"AGIP CAMPANIA"	S.N.A.M.	ITALY	VLCC	255,000	FENDERS	JAN '82	SIDES	500 sq.m.
"PANAMA"	E.A.C.	DENMARK	TANKER	33,000	FENDERS	JAN '82	TOPSIDES AND BOW	2,100/500 sq.m.
"SOLOGNE"	SFTP	FRANCE	TANKER	136,000	FENDERS	FEB '82	BOOTTOP	200 sq.m.
"ALMADRABA DOS"	A.R.C.A.	SPAIN	FISHING BOAT	1,000	FENDERS	FEB '82	DECK/TOPSIDES	600 sq.m.
"MATHILDE MAERSK"	AP MOELLER	DENMARK	CONTAINER	22,700	FENDERS	MAR '82	BOW	200 sq.m.
"AUSTRALIAN PROSPECTOR"	ANL	AUSTRALIA	BULKER	139,000	FENDERS	MAR '82	BOOTTOP	300 sq.m.
"KATENDRECHT"	VAN OMMEREN	HOLLAND	BULKER	28,000	FENDERS	MAR '82	BOOTTOP	900 sq.m.
"ESSO SEVERN"	ESSO	UK	TANKER	20,000	FENDERS & DECK DAMAGE	APR '82	DECK/ TOPSIDES	850/ 1,700 sq.m.
"NACELLA"	SHELL	GERMANY	TANKER	117,000	FENDERS	APR '82	BOW	300 sq.m.
"CASABLANCA"	DAMMERS VAN DER HEIDE	HOLLAND	CARGO	2,520	FENDERS	APR '82	BOOTTOP	400 sq.m.
"MAYA"	DAMMERS VAN DER HEIDE	HOLLAND	CARGO	2,520	FENDERS	APR '82	BOOTTOP	400 sq.m.
"PROTEKTOR"	LAEISZ	GERMANY	BULKER	80,000	FENDERS	MAY '82	BOOTTOP	2,700 sq.m.
"TEIGLAND"	MOGSTER	NORWAY	FISHING	500	FENDERS	MAY '82	TOPSIDES	[illegible] sq.m.

VESSEL NAME	SHIPOWNER	COUNTRY	VESSEL TYPE	DWT	CAUSE OF DAMAGE	DATE OF APPLICATION	VESSEL AREA	AREA COATED
"DON HUMBERTO"	SALEN	SWEDEN	TANKER	155,211	FENDERS	MAY '82	BOOTTOP/ TOPSIDES	400 sq.m.
"STARWORLD"	WORLDWIDE	HONG KONG	BULKER	43,000	CARGO	MAY '82	HOLD	600 sq.m
"PASADENA"	E.A.C.	DENMARK	TANKER	34,000	FENDERS	MAY '82	TOPSIDES	2,000 sq.m.
"MOORDRECHT"	VAN OMMEREN	HOLLAND	BULKER	45,000	FENDERS	MAY '82	BOOTTOP	1,000 sq.m.
"ALMADRABA TRES"	A.R.C.A.	SPAIN	FISHING BOAT	1,000	FENDERS	JUNE '82	DECK/TOPSIDES	2,000 sq.m.
"POLAR QUEEN"	GO RIEBER	CANADA	SUPPLY VESSEL	1,500 grt	ICE	JUNE '82	FLATS/SIDES	200 sq.m.
"DONAX"	SHELL	UK	TANKER	74,000	FENDERS	JUNE '82	BOOTTOP	2,700 sq.m.
"ARCTIC"	CANADA SS	CANADA	BULKER	28,000	ICE	JUNE '82	FLATS & SIDES	500 sq.m.
"TABORA"	DAL	GERMANY	CARGO	19,000	FENDERS	JUNE '82	BOOTTOP	1,000 sq.m.
"EKEN"	EKTANK	SWEDEN	TANKER	7,700	ICE	JUNE '82	BOW	200 sq.m.
"STAR HONG KONG"	WORLDWIDE	HONG KONG	BULKER	43,000	CARGO	AUG '82	HOLD	1,500 sq.m.
"HONAM JADE"	HONAM TANKERS	KOREA	TANKER	187,000	FENDERS	AUG '82	BOW	200 sq.m.
"GREYGARTH"	CORY SHIP TOWAGE	UK	TUG	140	FENDERS	AUG '82	TOPSIDES	100 sq.m.
"HUMBER ARM"	BERGESEN	NORWAY	RO-RO/ CARGO	7,200	ICE	AUG '82	UNDERWATER HULL	2,600 sq.m.
"BISSARUNI"	TORVALD KLAVENESS	NORWAY	BULKER/ BARGE	10,000	GROUNDING	AUG '82	FLATS	250 sq.m.
"FERNWAVE"	FEARNLEY EGER	NORWAY	LPG	12,000	FENDERS	SEPT '82	BOOTTOP	650 sq.m.
"ESSO CLYDE"	ESSO	UK	TANKER	20,000	FENDERS	SEPT '82	TOPSIDES	1,700 sq.m.
"GEOMITRA"	SHELL	UK	GAS CARRIER	37,500	FENDERS	OCT '82	TOPSIDES	240 sq.m.

VESSEL NAME	SHIPOWNER	COUNTRY	VESSEL TYPE	DWT	CAUSE OF DAMAGE	DATE OF APPLICATION	VESSEL AREA	AREA COATED
"VELMA"	DIETLEV SIMONSEN	NORWAY	TANKER	358,000	FENDERS	NOV '82	BOW	1,000 sq.m.
"GALAPAGOUS"	SALEN	SWEDEN	BULKER	23,300	FENDERS	OCT '82	BOOTTOP	300 sq.m.
"AUSTRALIAN PROGRESS"	ANL	AUSTRALIA	BULKER	140,000	FENDERS	NOV '82	SIDES	200 sq.m.
"CALAFIA"	DAMMERS VAN DER HEIDE	HOLLAND	CARGO	2,520	FENDERS	NOV '82	BOOTTOP	325 sq.m.
"GADINIA"	SHELL KOSAN	JAPAN	LNG	37,000	FENDERS	NOV '82	TOPSIDES	200 sq.m.
"LAURA CHRISTINA"	DAMMERS VAN DER HEIDE	HOLLAND	CARGO	2,520	FENDERS	NOV '82	BOOTTOP	320 sq.m.
"CHEVRON COLORADO"	CHEVRON	USA	TANKER	40,000	ICE	DEC '82	BOW	200 sq.m.
"MOBIL MAGNOLIA"	MOBIL	UK	TANKER	280,000	FENDERS	DEC '82	SIDES	250 sq.m.
"WESTERN LION"	MARITIME OVERSEAS	USA	TANKER	269,000	FENDERS	DEC '82	SIDES	200 sq.m.
"ASIAN PEARL"	ASIA AUSTRALIA	HONG KONG	CONTAINER	24,300	FENDERS	DEC '82	BOOTTOP	350 sq.m.
"ANTRIM PRINCESS"	SEALINK	UK	FERRY	3,600	GROUNDING	JAN '83	FLATS	1,200 sq.m.
"ACADIA"	ITALIA DI NAVIG	ITALY	CONTAINER	19,000	FENDERS	FEB '83	BOOTTOP	500 sq.m.
"ZLATNI PIASATZI"	OKEANSKY RIBOLOV	BULGARIA	REEFER	5,200	FENDERS	FEB '83	BOOTTOP	900 sq.m.
"NEDDRILL 2"	NEDDRILL	HOLLAND	DRILL SHIP	12,300	FENDERS	FEB '83	TOPSIDES	240 sq.m.
"GAS AL MINAGISH"	KOTC	KUWAIT	TANKER	47,500	FENDERS	FEB '83	BOOTTOP	1,400 sq.m.
"COAST RANGE"	WEST COAST	USA	TANKER	42,400	FENDERS	FEB '83	BOW	600 sq.m.
"SUMBAWA"	EAC	DENMARK	BULKER	23,000	FENDERS	MAR '83	BOOTTOP	750 sq.m.
"KINOKUNI MARU"	SHINYEI STEAMSHIP	JAPAN	BULKER	62,000	CARGO	MAR '83	HOLD	300 sq.m.
"GOULDIA"	SHELL KOSAN	JAPAN	LNG	[illegible],000	FENDERS	MAR '83	TOPSIDES	[illegible] sq.m.

VESSEL NAME	SHIPOWNER	COUNTRY	VESSEL TYPE	DWT	CAUSE OF DAMAGE	DATE OF APPLICATION	VESSEL AREA	AREA COATED
"JAN WILLEM"	DAMMERS VAN DER HEIDE	HOLLAND	CARGO	2,500	FENDERS	MAR '83	BOOTTOP	200 sq.m.
"JOHN A McCONE"	CHEVRON	USA	TANKER	150,000	FENDERS	MAR '83	BOW	500 sq.m.
"YANBU PROGRESS"	INTEROCEAN	UK	TANKER	215,000	FENDERS	MAR '83	BOOTTOP	400 sq.m.
"FARNES"	JEBSENS	UK	BULKER	12,400	FENDERS	MAR '83	UNDERWATER HOLD	3,500 sq.m.
"KHANNUR"	GOLAR GAS TRANS	UK	LNG	72,000	CARGO	APR '83	BOOTTOP	200 sq.m.
"KANSAS GETTY"	GETTY MARINE CORP	USA	TANKER	81,000	FENDERS	APR '83	TOPSIDES/SIDES	400 sq.m.
"LA PAMPA"	BURIES MARKS	UK	CARGO	16,000	CARGO	APR '83	HOLD	300 sq.m.
"PLAYA DE RIAZOR"	NAVIERA FIERRO	SPAIN	TANKER	102,913	FENDERS	APR '83	BOOTTOP	200 sq.m.
"HOEGH HOOD"	LEIF HOEGH	NORWAY	TANKER	249,000	FENDERS	APR '83	BOOTTOP/BOW	2,600 sq.m.
"KITEN"	OKEANSKY RIBOLOV	BULGARIA	REEFER	5,200	FENDERS	APR '83	UNDERWATER HULL	1,000 sq.m.
"DRONNING MARGARETHE II"	DANISH RAIL	DENMARK	FERRY	5,600 grt	FENDERS	APR '83	UNDERWATER	2,000 sq.m.
"VISBY"	REDERI AB GOTLAND	SWEDEN	FERRY	15,000 grt	ICE	APR '83	UNDERWATER HULL	4,000 sq.m.
"CIELO DI NAPOLI"	D'AMICO SOC	ITALY	TANKER	32,800	FENDERS	MAY '83	BOOTTOP/ TOPSIDES	4,000 sq.m.
"KOREA PIONEER"	CHO YANG SHIPPING	KOREA	LOG CARRIER	37,000	LOG DAMAGE	MAY '83	SIDES	600 sq.m.
"GOTLAND"	REDERI AB GOTLAND	SWEDEN	FERRY	6,600 grt	ICE	MAY '83	UNDERWATER HULL	2,000 sq.m.

VESSEL NAME	SHIPOWNER	COUNTRY	VESSEL TYPE	DWT	CAUSE OF DAMAGE	DATE OF APPLICATION	VESSEL AREA	AREA COATED
"KIELDRECHT"	VAN OMMEREN	HOLLAND	BULKER	28,000	CARGO	MAY '83	HATCH COAMINGS	600 sq.m.
					FENDERS		UNDERWATER HULL	2,000 sq.m.
"TONSINA"	KEYSTONE SHIP	USA	TANKER	125,000	FENDERS	MAY '83	TOPSIDES	400 sq.m.
"ARCTIC TOKYO"	ARCTIC LNG	UK	LNG	33,000	ICE	MAY '83	UNDERWATER HULL	1,000 sq.m.
"STAR MAGNATE"	WORLDWIDE	HONG KONG	BULKER	43,000	CARGO	MAY '83	HOLD	500 sq.m.
"BOREE"	TOTAL	FRANCE	TANKER	283,000	FENDERS	MAY '83	BOW	1,500 sq.m.
"ERVILIA"	SHELL	UK	TANKER	31,000	FENDERS	MAY '83	BOOTTOP	1,500 sq.m.
"ARCTIC"	CANADA SS LINES	CANADA	BULKER	28,000	ICE	MAY '83	SIDES	1,000 sq.m.
"OCEAN EVER"	PAN OCEAN BULK	KOREA	BULKER	46,000	FENDERS	MAY '83	BOOTTOP	850 sq.m.
"RAS AL ZOUR"	KOTC	KUWAIT	TANKER	28,000	FENDERS	MAY/JUNE '83	BOOTTOP	800 sq.m.
"OVERSEAS ALASKA"	MOC	USA	TANKER	63,000	FENDERS	JUNE '83	BOOTTOP	1,500 sq.m.
"ARCTIC SHIKO"	FEDERAL COM[illegible]	CANADA	SUPPLY VESSEL	1,200	FENDERS	JUNE '83	WHOLE BOTTOM	400 sq.m.
"PHAROS"	LAEISZ	GERMANY	BULKER	75,000	FENDERS	JUNE '83	BOOTTOP	200 sq.m.
"OVERSEAS MARILYN"	MOC	USA	BULKER	25,500	FENDERS	JUNE '83	TOPSIDES	280 sq.m.
"BLUE RIDGE"	UNION OIL CO	USA	TANKER	42,000	FENDERS	JUNE '83	BOW	500 sq.m.
"SEASCAPE"	SALEN	SWEDEN	TANKER	362,000	FENDERS	JUNE '83	BOOTTOP	200 sq.m.
"PATTAYA"	EAC	DENMARK	TANKER	33,000	FENDERS	JUNE '83	BOOTTOP	500 sq.m.
"SHOEI MARU"	IINO KAIUN	JAPAN	TANKER	61,000	FENDERS	JUNE '83	SIDES	400 sq.m.
"BORINGIA"	EAC	DENMARK	CONTAINER	[illegible],000	FENDERS	JUNE '83	BOOTTOP	[illegible]0 sq.m.

VESSEL NAME	SHIPOWNER	COUNTRY	VESSEL TYPE	DWT	CAUSE OF DAMAGE	DATE OF APPLICATION	VESSEL AREA	AREA COATED
"CORNUCOPIA"	WEST COAST SHIP	USA	GAS CARRIER	24,000	FENDERS	JULY '83	TOPSIDES/BOW	400 sq.m.
"SALVADOR"	IVARANS RED.	NORWAY	CONTAINER	15,000	FENDERS	JULY '83	WHOLE BOTTOM	4,000 sq.m.
"VERSALIUS"	CMB	BELGIUM	BULKER	134,000	CARGO	JULY '83	HOLDS	13,500 sq.m.
"LARK FIELD"	BURIES MARKES	UK	BULKER	39,000	FENDERS	JULY '83	BOOTTOP	1,000 sq.m.
"YATES TRADER"	MARATHON	UK	TANKER	138,000	FENDERS	JULY '83	SIDES/BOOTTOP/ TOPSIDES	12,000 sq.m.
"ATALANTA"	SEVEN SEAS	GREECE	BULKER	22,000	FENDERS	JULY '83	TOPSIDES	2,000 sq.m.
"RIO SULACO"	FYFFES GROUP	UK	CARGO	6,500	FENDERS	JULY '83	BOOTTOP	800 sq.m.
"SEA SAGA"	SALEN	SWEDEN	TANKER	357,000	FENDERS	JULY '83	BOOTTOP	250 sq.m.
"ORKNEY"	WALLEMS	HONG KONG	BULKER	23,000	FENDERS	JULY '83	BOOTTOP	500 sq.m.
"GEROI SHIPKI"	USSR	USSR	RO-RO	13,000	FENDERS	JULY '83	BOOTTOP	850 sq.m.
"FIONIA"	EAC	DENMARK	CONTAINER	20,000	FENDERS	JULY '83	BOOTTOP	500 sq.m.
"ROALD AMUNDSEN"	BAKKEVIK EINAR	NORWAY	GAS CARRIER	4,400	ICE	JULY '83	WHOLE BOTTOM	1,200 sq.m.
"VLADIMIR" KAPRILOV"	USSR	USSR	BULKER	80,000	CARGO	AUG '83	HOLDS	10,000 sq.m.
"SEAFORTH ATLANTIC"	FEDERAL COM.	CANADA	SUPPLY	1,000	ICE	AUG '83	TOPSIDES	200 sq.m.
"BAIKO MARU"	SANKO	JAPAN	OBO	83,800	CARGO	AUG '83	HOLDS	11,000 sq.m.
"SEA SONG"	SALEN	SWEDEN	TANKER	357,000	FENDERS	AUG '83	SIDES	400 sq.m.
"LANKA SRIMANI"	CEYLON SHIPPING	SRI LANKA	CONTAINER	9,000	FENDERS	AUG '83	BOOTTOP	440 sq.m.
"BORA UNIVERSAL"	CULLEN	UK	CARGO	9,000	FENDERS	AUG '83	BOW	300 sq.m.
"OVERSEAS ARCTIC"	MOC	USA	TANKER	63,000	FENDERS	AUG '83	TOPSIDES	1,700 sq.m.
"GARRISON POINT"	HUDSON SS	UK	CARGO	12,300	FENDERS	AUG '83	TOPSIDES	1,000 sq.m.

VESSEL NAME	SHIPOWNER	COUNTRY	VESSEL TYPE	DWT	CAUSE OF DAMAGE	DATE OF APPLICATION	VESSEL AREA	AREA COATED
"ENTALINA"	SHELL	UK	TANKER	31,000	FENDERS	AUG '83	TOPSIDES/BOW/ BOOTTOP	3,000 sq.m.
"BALTIC EAGLE"	UNITED BALTIC	UK	RO-RO	9,500	ICE	AUG '83	BOOTTOP	500 sq.m.
"INCA"	DAMMERS VAN DER HEIDE	HOLLAND	CARGO	2,500	FENDERS	AUG '83	BOOTTOP	250 sq.m.
"HAVSO"	CARLSSON H.	SWEDEN	CARGO	3,200	ICE	AUG '83	FLATS/SIDES	500 sq.m.
"CONDATA"	FYFFES GROUP	UK	CARGO	10,000	ICE	AUG '83	BOOTTOP	1,000 sq.m.
"ESSO PORT DICKSON"	ESSO	SINGAPORE	TANKER	21,500	FENDERS	SEPT '83	TOPSIDES	700 sq.m.
"SMIT-LLOYD 44"	SMIT-LLOYD BV	HOLLAND	TUG	1,000	FENDERS	SEPT '83	WHOLE BOTTOM	900 sq.m.
"LANKA SRIMATHE"	CEYLON SHIP	SRI LANKA	CONTAINER	9,000	FENDERS	SEPT '83	BOOTTOP	850 sq.m.
"FP CONVEYOR"	FAC	DENMARK	BULKER	39,000	FENDERS	SEPT '83	SIDES/BOOTTOP HOLDS	2,400 sq.m. 6,100 sq.m.
"MATHILDA"	DAMMERS VAN DER HEIDE	HOLLAND	CONTAINER	3,500	FENDERS	SEPT '83	BOOTTOP	200 sq.m.
"DISCOVERY"	NAT. ENV. COUN.	UK	RESEARCH	2,000	FENDERS	SEPT '83	BOOTTOP	200 sq.m.
"CORNER BROOK"	SIG. BERGESEN	NORWAY	CARGO	7,200	ICE	SEPT '83	WHOLE BOTTOM	2,500 sq.m.
"KOTUKU"	UNION SS	NEW ZEALAND	TANKER	26,000	FENDERS	SEPT '83	BOOTTOP	800 sq.m.
"CREUSE"	SNCDV	FRANCE	CARGO	16,000	FENDERS	SEPT '83	WHOLE BOTTOM	4,000 sq.m.
"TRANSVAAL"	DAL	GERMANY	CONTAINER	50,000	FENDERS	SEPT '83	SIDES/BOW/ BOOTTOP	2,600 sq.m.
"OMOA"	FYFFES GROUP	UK	CARGO	8,200	FENDERS	SEPT '83	BOOTTOP	1,200 sq.m.
"SKAUGRAN"	SKAUGEN	NORWAY	RO-RO	42,000	FENDERS	OCT '83	SIDES/BOOTTOP	6,000 sq.m.

VESSEL NAME	SHIPOWNER	COUNTRY	VESSEL TYPE	DWT	CAUSE OF DAMAGE	DATE OF APPLICATION	VESSEL AREA	AREA COATED
"ATLANTIC FOREST"	MOSVOLD	NORWAY		50,000		OCT '83	STERN	
"GARDEN STATE"	SCORPIO	USA	OBO	47,900	FENDERS	NOV '83	BOOTTOP	2,250 sq.m.
"GARDEN NEPTUNE"	SCORPIO	USA	OBO	48,900	FENDERS	NOV '83	BOOTTOP	2,000 sq.m.
"ESSO FORTH"	ESSO	UK	TANKER	77,400	FENDERS	NOV '83	TOPSIDES	4,500 sq.m.
"GARDENGATE"	SCORPIO	USA	OBO	12,000	FENDERS	NOV '83	BOOTTOP	1,600 sq.m.
"AFRAN ZODIAC"	GULF TRADING	USA	TANKER	230,000	FENDERS	NOV '83	BOOTTOP/TOPSIDE	600 sq.m.
"HAN CHUAN"	COSCO	PRC	CARGO	11,000	FENDERS	NOV '83	BOOTTOP	1,000 sq.m.
"LEDA"	SHELL	FRANCE	TANKER	282,000	FENDERS	NOV '83	BOW	200 sq.m.
"PURITAN"	LAEISZ	GERMANY	BULKER	9,700	FENDERS	NOV '83	BOOTTOP	700 sq.m.
"AGIP LAZIO"	SNAM	ITALY	TANKER	254,659	FENDERS	DEC '83	BOOTTOP/TOPSIDE	2,000 sq.m.
"SARGODHA"	E.A.C.	DENMARK	CARGO	23,700	FENDERS	DEC '83	SIDES/BOOTTOP	3,500 sq.m.
"HEBBLE SAND"	ASS. BR. PORTS.	UK	DREDGER	1,000	SAND	DEC '83	WHOLE BOTTOM	600 sq.m.
"SIMBA"	E.A.C.	DENMARK	CARGO	23,700	FENDERS	DEC '83	SIDES/BOOTTOP	3,500 sq.m.
"NORD POL"	NORDTRAMP A/S	NORWAY	BULKER	34,000	FENDERS	DEC '83	BOOTTOP	1,400 sq.m.
"CAIRNSMORE"	INDOCHINA SP.	HONG KONG	BULKER	35,000	FENDERS	DEC '83	BOOTTOP	200 sq.m.
"AFRAN HORIZON"	GULF TRADING	USA	TANKER	124,000	FENDERS	DEC '83	BOOTTOP	1,200 sq.m.
"MYRICA"	COGEMA	MONACO		21,000	FENDERS	DEC '83	SIDES/BOOTTOP	3,500 sq.m.
"PHAROS"	LAEISZ	GERMANY	BULK	75,000	FENDERS	DEC '83	BOOTTOP	2,400 sq.m.
"HOEGH FAVOUR"	LEIF HOEGH	NORWAY	TANKER	82,000	FENDERS	DEC '83	SIDES/BOOTTOP	1,800 sq.m.
"UMM AL ROUS"	KOTC	KUWAIT	TANKER	47,169	FENDERS	DEC '83	BOOTTOP	2,000 sq.m.

VESSEL NAME	SHIPOWNER	COUNTRY	VESSEL TYPE	DWT	CAUSE OF DAMAGE	DATE OF APPLICATION	VESSEL AREA	AREA COATED
"LAGOVEN INCARTE"	LAGOVEN S.A.	VENEZUELA	TANKER	15,760	FENDERS	JAN '84	BOOTTOP/ TOPSIDES	2,500 sq.m.
"ILHA DO FOGO"	PESCA BRAVA	PORTUGAL	FISHING	400	FENDERS	JAN '84	WHOLE BOTTOM	500 sq.m.
"TAEPING"	ANGLO-EASTERN	HONG KONG	CARGO	10,500	FENDERS	JAN '84	BOOTTOP	830 sq.m.
"BLUESTREAM"	FYFFES GROUP	UK	REEFER	6,000	FENDERS	JAN '84	BOOTTOP	900 sq.m.
"SMIT LLOYD 43"	SMIT-LLOYD	HOLLAND	SUPPLY	800	FENDERS	FEB '84	WHOLE BOTTOM	900 sq.m.
"FLEET WAVE"	FLEETWOOD LTD	HONG KONG	CARGO	6,000	FENDERS	FEB '84	SIDES/BOOTTOP	1,600 sq.m.
"SONJA"	OT-REDERIERNA	SWEDEN	TANKER	32,000	FENDERS	FEB '84	BOOTTOP	1,000 sq.m.
"CIELO DI GENOVA"	D'AMICO	ITALY	CONTAINER	32,000	FENDERS	MAR '84	BOOTTOP/ TOPSIDES	3,450 sq.m.
"AFRAN SKY"	DENHOLM SHIPPING	UK	TANKER	150,441	FENDERS	MAR '84	BOOTTOP TOPSIDES	200 sq.m.
NORUECA"	INST.NAC.DE.INV.	PORTUGAL	FISHING	950	FENDERS	MAR '84	WHOLE BOTTOM	1,300 sq.m.
"AL FUJAIRAH"	UNITED ARAB SHIPPING	KUWAIT	CARGO	15,446	FENDERS	APR '84	BOOTTOP	1,400 sq.m.

APPENDIX II

COATING METHOD OF APPLICATION

INTERNATIONAL PAINTS/TEKNOS-MAALIT OY

INERTA 160

TEKNOS-MAALIT OY
PAINT MANUFACTURERS 00101 HELSINKI 10, P.O. BOX 107

DATA SHEET 119
EE
1983-04-19

INERTA 160 Epoxy Coating

TYPE

A two pack liquid epoxy resin based paint, almost free of solvent.

AREAS WHERE USED

Designed for use on steel (Paint System K 31/E 500). Also suitable for concrete.

SPECIAL PROPERTIES

Good adhesion to blast-cleaned steel and excellent abrasion resistance are characteristic of INERTA 160. Consequently, the coating is suitable for use on structures subject to heavy mechanical abrasion. Particularly suited for use as hull coating on ships destined for service in ice. The coating prevents pitting in the hull plating and reduces ice resistance. Other areas of application are cooling water and inlet pipings in power plants, gratings and sluices, industrial conveyors, dump waggons, etc.

The coating possesses good chemical resistance. Resistance to oil, grease and petrol products is good even on immersion. Strong solvents cause the coating to swell.

INERTA 160 can be used in nuclear power plants, since its resistance to radiation is good and the coating is easy to decontaminate.

INERTA 160 is to be applied by a two-component spray, which provides a film thickness of 500 microns in a single operation.

TECHNICAL DATA

Mixing ratio by volume	Base 2 parts Hardener 1 part
Pot life at +23°C	Undiluted mixture: 20 min.
Volume solids	Over 96%

Recommended film thickness and theoretical spreading rate

System	Dry film	Wet film	Theoretical spreading rate
K 31	500 mcs.	Abt. 500 mcs.	Abt. 2 sq.m./lit.

Practical spreading rate	Dependent on application technique, surface conditions, wastage, etc.

P.T.O.

Litre weight	Mixture	1.4 kg
	Base	1.6 kg
	Hardener	1.1 kg
Drying time at +23°C	Dust free	4 h
	Tack free	12 h
	Fully cured	7 d
	Can be recoated as soon as the previous coat is gelled. Maximum interval between coats is 24 hours.	
Clean up	THINNER 9506 is recommended for cleaning the two-component spray.	
Viscosity	Thixotropic	
Finish	Gloss	
Colours	White, black and a limited range of T-M Industrial Paint Colours	
Packages	Base:	20 litres
	Hardener:	10 litres

DIRECTION FOR USE

Surface preparation

General cleaning: Any contamination of the surface that may hamper the removal of rust and the application of paint, should first be removed by appropriate cleaning methods.

Ice, concrete, mortar and other solid residues should be removed by chipping, scraping or brushing. Salt deposits and other water soluble contaminants should be cleaned from the surface by washing down with water and brush, by means of high pressure water, steam jets or emulsifier. Surfaces contaminated by grease and oil can be washed down with alkali solution, emulsifier or solvent.

Removal of rust: After general cleaning steel surfaces should be blast-cleaned to Sa 2 1/2 (SIS 055900). (The same applies to shop-primed surfaces.)

Concrete: The concrete must be at least 4 weeks old, solid and well-cured. The water content of the top layer must not exceed 4% by weight. Any spatter or irregularities in the surface should be smoothed down by grinding. Loose cement, sand and dust should be brushed away. Surfaces contaminated by dirt and grease should be washed down with detergent or solvent. Tight glossy laitence if present should be removed by acid etching, grinding or blast-cleaning.

Stopping up	Severely pitted steel, such as hull plating, can be stopped up with INERTA 160 FILL. The stopper is to be applied by a two-component spray and smoothed immediately by a broad putty knife (width 20 to 30 cms.). Big cavities if present in concrete surfaces should be repaired with cement mortar immediately after dismounting the mould. Before the application of INERTA 160, all holes present should be filled up, and if required, the whole surface stopped up with water-borne EPIREX-AKVA-FILL Epoxy Stopper. INERTA 160 FILL can also be used.
Painting conditions	The surface to be coated must be dry. The temperature of the ambient air, the surface and the paint should be over +10°C and the relative air humidity below 80% during the application and drying period.
Application method	By a two-component spray, e.g. Graco Hydra-Cat, equipped with heating system; turn-nozzles 0.021 - 0.026".
Application	When the application is done by a two-component spray, the paint must be kept at a temperature of +20 to +25°C before use so that the components are fluid enough for the feed pumps. The ratio of the dosage pump must be 2 : 1. The heating of components should be adjusted so that the temperature in the gun is +40 to +50°C. Then the pot life of the mixture is 5 min. If required, also the hoses should be heated. The film thickness should be controlled by a wet film gauge. The feed pump pressure and the consumption of components should be controlled to ensure the correct mixing ratio. To fill up the pores in concrete surfaces, the paint should first be applied in a coat of 200 to 300 microns and smoothed by brush or rubber blade over porous areas. Immediately thereafter, another coat is to be applied in order to achieve the full film thickness of 500 microns. Directions given by manufacturers for use of two-component sprays should be followed.
Touch-up coats	When used for touch-up and maintenance of small areas, INERTA 160 can be diluted by 7%. The application is to be done by airless spray with great proportion of pressure, or by brush. The components should be mixed immediately before use in ratio of 2 parts Base to 1 part Hardener by volume and stirred thoroughly by drilling machine. Thereafter the mixture is to be thinned by adding 0.2 parts THINNER 9506 or 9514 by volume. The pot life of the mixture is then about 40 min. (at +23°C). (NOTE! Also the amount and temperature of the mixture affect the pot life. If the paint sets in the gun, the spray is damaged.)

P.T.O.

The components should be mixed and stirred carefully. Careless stirring or incorrect mixing ratio results in imperfect curing and impaired film properties. When diluted paint is used, the dry film thickness of 500 microns is achieved by applying two coats with 300 microns wet film each. The second coat can be applied as soon as the previous one is gelled, and within 24 hours at the latest.

SAFETY PRECAUTIONS

Flash point:
Base +85°C
Hardener +63°C
LT Group 0

Ready mixed paint

Contains:

Aliphatic polyamine epoxy adduct	15 - 50%
Liquid epoxy resin	15 - 50%

Injurious to the health by inhalation and skin contact or if swallowed. Exposure to liquid epoxy resin may cause allergy of skin and respiratory organs.

Must not come into contact with skin, eyes or respiratory organs. Keep out of the reach of children.

Painters should wear sensible protective clothing, gloves and masks.

Medical first aid

By skin contact: Remove any spatter of paint on the skin with soap and water. Apply then suitable cream to the skin.

By eye contact: Flush immediately with fresh water for 15 min. Seek medical attention if required.

On request, a product information sheet listing the components used is sent to Authorities for Working Safety.

APPLICATION OF INERTA 160 AND DIRECTION FOR USE OF HYDRA CAT SPRAY EQUIPMENT

1.
BEGINNING OF THE WORK

Do not use cold paint, but heat it up to about +20°C. Otherwise the application will be slowed up.

1.1 Check the supply of compressed air and the earth connections of the spray.

1.2 Make sure that there is a sufficient amount of cleaner in the solvent cistern. See to that the solvent pump is ready for operation.

1.3 Switch on the spray heaters and heatable hoses. Adjust the heating at first to the full and then to about +70°C during the application.

1.4 Fill the paint vessels and protect them with covers so that no foreign matter can get into the paint to disturb the work.

1.5 Switch on the circulation. Let the paint circulate for 15 to 30 min. The paint should get heated to +60 to +70°C during the circulation. Spraying will not be successful if the paint is not hot enough in the pistol, too. The circulation should take place through the whole set of conveying hoses.

1.6 When spraying is started, switch off the circulation and rise the pressure of the main pump up to 200 to 300 bars.

1.7 Turn the mixing handle to the spraying position. The solvent faucet must be turned off.

1.8 Let all thinner run away from the pistol and hose carefully. Note! EARTH CONNECTIONS. Check that hot paint enters the pistol; otherwise the application will not be successful.

2.
INTERRUPTION OF THE WORK

2.1 Turn off the mixing handle.

2.2 Turn on the solvent faucet.

2.3 Let solvent run through the mixing tube and to the hose of the pistol.

2.4 Reduce the heating to +30 to +40°C.

2.5 Drop the pressure of the main pump.

2.6 Switch on the circulation.

3. TERMINATION OF THE WORK

3.1 If there will be a lengthy standstill, wash the whole spray equipment with solvent.

3.2 In the event of shorter standstill (e.g. two days), the paint components may be left in the pump and feeder vessels stored well protected in a warm place.

3.3 Most important at interruptions or termination of the work is that the MIXING TUBE, HOSE and PISTOL are always cleaned properly. The washing time should be 15 min. at least.

3.4 When spraying is terminated, clean the feeder pump filters. It may be necessary during a long spraying period to wash the mixing tube in case it does not give a sufficient amount of paint.

3.5 THE FEEDER VESSELS MUST BE FULL ENOUGH OF PAINT DURING THE SPRAYING. The pump must not be let suck mere air, because it will at once alter the mixing ratio, etc. Should the pump suck mere air, stop the work and remove air from the hoses by aid of circulation.

4. SPRAYING

Wear the protective clothing, gloves and masks recommended and put them on before the start of the work.

4.2 Control the wet film thickness as work proceeds and aim at an even film thickness by cross-spraying.

4.3 If the pistol does not give a satisfactory spray pattern, check the pressure and the temperature of paint. If the nozzle produces thick stripes, there is risk of runnings.

4.4 It is important to control the pressure meters of the main pump continuously. The both meters should show a reading of 200 to 300 bars. If one of the meters indicates reduced pressure, BREAK OFF THE WORK and investigate the cause of it.

4.5 Control the consumption of paint. The consumption must be 10 litres Hardener to 20 litres Base.

4.6 Oil the piston-rods of the pump regularly.

4.7 In case you must use too high pressure, check the packings and filters of the dosage pump.

4.8 In the event of an unexpected disturbance or break, LET ALWAYS FIRST SOLVENT ENTER THROUGH THE MIXING TUBE UP TO THE PISTOL. Then you have time to find out what the matter is.

RELIANCE UNIVERSAL

ZEBRON

April 1, 1985

STANDARD MARINE SPECIFICATION

SURFACE PREPARATION and APPLICATION

of

ZEBRON (tm) 1864 COATING

I. GENERAL

1.0 This specification covers the following coating system:

Coat No.	Product	Dry Film Thickness (DFT)
(a)	Zebron 1864	1.0 mm (40 mils) minimum

1.1 Zebron 1864 is a 100% solid, solventless polyurethane marketed by Reliance Universal (BC) Ltd., 20100 No. 10 Highway, Langley, B.C., Canada V3A 5E7, telephone: (604) 534-7951 and applied by authorized applicators.

1.2 This specification covers only the spray application of the material. Hand mixing and trowelling or spraying/trowelling with subsequent top coating of the material are not covered. Only application to steel surfaces and, in particular ship hulls, decks and internals, is intended.

II SURFACE PREPARATION

2.0 All surfaces to be coated shall be blasted using slag grit in preparation for application of the coating. Where a prescribed area is to be coated, the grit blasting shall extend at least 50 mm (2") on each end beyond the area to be coated. When blasting is completed, the surface of the steel must be an even grey colour as defined by the Steel Structures Painting Council (S.S.P.C.) in Surface Preparation Specification No. 10, Blast Cleaning to 'near white' cleanliness, until at least 95% of each element of surface area is free of all visible residues. The resulting surface roughness profile shall be a minimum of 75 microns (3 mils). Only grit capable of cutting a sharp 75 micron (3mil) profile is acceptable. Silica Sand can be used to obtain the desired standard of cleanliness but is not acceptable for cutting the required profile.

2.1 The underside and narrow edges of all angles, weld beads, pits and structural members must be blasted to the same surface condition specified in 2.0. All surfaces must be completely cleaned of blasting products when blasting is completed. Excessively high asperities, including rough welds, corrosion undercutting of welds and other excessively sharp edges, shall be ground smooth prior to blasting and coating.

2.2 All surfaces to be coated must be completely dry, free of moisture, soil, dust and grit at the time the coating is applied.

2.3 The total area grit blasted shall extend 50 mm (2") past the area which can be cleaned and coated for that given day. This means that no area shall be allowed to sit overnight with a grit blasted exposed surface.

2.4 Areas so exposed to rain or moisture as to develop flash rust shall be given a sweep blast to return them to the originally blasted condition.

2.5 Should the area to be coated exceed that which can be accomplished in a single application, the Zebron coating must be feathered down to the steel substrate at the completion of each working day.

2.6 Blasting adjacent to freshly coated steel shall not commence until the Zebron has cured to a tack-free condition. Blasting should then be initiated 300 mm (12") onto existing Zebron.

2.7 All blasting onto existing Zebron must be directed from the coated surface to the adjacent substrate rather than from the substrate onto the coating.

2.8 Before coating, all areas of the dry dock, including the floor, scaffolding, walkways and decks within 50 feet of any surface to be coated, shall be swept or otherwise cleaned of grit or grit blasting product. Prevention of contamination by wind blown dust is the consideration. This procedure must be carried out prior to vacuuming or blowing down the surface to be coated.

2.9 Where bare ground and high winds exist, the surrounding area should be wetted to a reasonable extent.

III. APPLICATION

3.0 Neither condensation, precipitation, nor any other forms of contamination will be acceptable on the blasted surface prior to coating. Surfaces subject to any of these conditions shall be cleaned with fresh water if necessary and sweep blasted to return the surface to SA 2.5 cleanliness.

3.1 The acceptable temperature range for application of Zebron 1864 is 3°C (38°F) to 38°C (100°F). The acceptable relative humidity range is 0 to 80%. The substrate temperature must be a minimum of 3°C (5°F) above dew point temperature before proceeding with the coating operation. Application temperature can be lower if substrate is heated.

3.2 Zebron 1864 shall be applied to the specified dry film thickness (DFT) in a single application using ZebraCat high pressure airless spraying equipment or approved equal. Wet film measurements shall be continuously performed to ensure close adherence to the thickness specification.

3.3 Zebron can be overcoated without the need for an additional tie coat. Should the overcoating interval exceed eight (8) hours, the surface should be blast roughened prior to application of the top coat.

3.4 Scaffolding and items such as hoses, cable braces, etc. not attached to the vessel shall be a minimum of 457 mm (18") from the surface to be coated or placed so as not to interfere with the space normally required for a spray gun operation.

3.5 A minimum of 48 hours curing above 10°C is required prior to putting the vessel in service. 96 hours curing time is desirable when atmospheric conditions are below 10°C.

IV. APPEARANCE OF FINISHED COATING

4.0 The finished coating shall be generally smooth and free of protuberances or holidays. All surfaces shall have the required minimum dry film thickness. In general, the surface roughness of the coating shall not exceed that of the base or substrate material. The finished coating film shall be free of runs, sags or other surface discontinuities.

4.1 The applicator shall exercise every reasonable precaution to assure proper application of the coating and satisfactory protection of the steel surface.

V. INSPECTION

5.0 The quality of all blasted surfaces, including cleaning of blast grit from these surfaces, will be inspected by a Reliance technician or appointed representative prior to the application of Zebron. Non-acceptance to be given by said representative to the owner and building yard representatives.

5.1 A Reliance technician or appointed representative will inspect the completed job and notify vessel owner and/or yard representatives of the degree of quality as related to the quality standards outlined by Reliance in their specification.

VI. SAFETY PRECAUTIONS

6.0 The contractor or yard will provide safe and secure scaffolding for ready access to work areas.

6.1 Other contract services will be halted as necessary so as not to interfere with the work flow of the Zebron application.

6.2 Zebron is harmful if absorbed through skin, inhaled or swallowed. It is a skin and eye irritant.

Use only with adequate ventilation. Do not breath vapor or spray mist. Do not get on skin, in eyes, or on clothing. Wear eye protection and protective clothing. Wear a properly fitted, air supplied respirator (NIOSH/MSHA approved) during and after application while exposed to fumes or spray mist. Follow respirator manufacturer's directions for respirator use.

Wash thoroughly with soap and water after handling.

FIRST AID: If inhaled, remove to fresh air. If breathing is difficult give oxygen. In case of contact: EYES - immediately flush eyes with plenty of water for at least 15 minutes; SKIN - wash exposed skin area with soap and water while removing contaminated clothing and shoes. CALL A PHYSICIAN. Wash clothing before reuse. Thoroughly clean contaminated shoes.

Keep Zebron container closed when not in use. In case of spillage absorb with inert material and dispose of in accordance with applicable regulations.

6.3 No open flames, smoking or welding will be allowed in the immediate vicinity of the ship or on board during the application of Zebron.

6.A All personnel on applicating crew shall be informed of yard regulations regarding smoking, auto traffic restrictions, meaning of warning bells, horns and whistles, fire warnings and restricted areas.

VII. EQUIPMENT

7.0 ZebraCat (tm) ultra high pressure spray equipment or equal must be used to apply Zebron coating systems in accordance with Reliance's recommendations and specifications.

VIII. MATERIALS

8.0 Zebron containers must be kept sealed prior to use. Product exposed to the atmosphere must be protected with a blanket of nitrogen gas.

8.1 No amount of Zebron shall be given, sold or exchanged for any consideration to any person without express written permission from Reliance Universal (BC) Ltd.

8.2 Cleaning Solvent: Zebron 480-80 Equipment Wash

IX. SUBSTRATE TYPES

9.0 This specification is applicable to standard steels as would normally be expected to be used on ______________________________.

9.1 Exotic metals, stainless steel or other special steel alloys may require different consideration as to surface preparation and Zebron formulations. Notification of the use of such metals must be made to Reliance Universal (BC) Ltd. in writing prior to the application of Zebron.

X. INSURANCE

10.0 The contractor shall provide all necessary third party liability insurance to adequately protect Reliance personnel and equipment on site or in transit to the site.

HEMPEL'S MARINE COATINGS

HEMPADUR 3555

HEMPEL

Hempel's Industrial Coatings

May 1984

APPLICATION INSTRUCTIONS

HEMPADUR* MULTI-STRENGTH 3555
HEMPADUR* MULTI-STRENGTH 3564

SCOPE:

This application instruction covers surface preparation, application equipment and application of HEMPADUR MULTI-STRENGTH 3555 and 3564.

SURFACE PREPARATION:

Steel:

Heavily scaled surfaces may be descaled mechanically prior to blasting.

Rough welds and sharp edges should be ground and rounded off prior to blasting. Weld splatter to be removed.

Grease, oil, fats and other contaminants have to be removed prior to blasting.

All steel surfaces to be protected must be abrasive grit-blasted to minimum "near white metal", SIS 055900, Sa 2½.

For very severe service conditions abrasive blasting to "white metal", Sa 3, can be necessary.

The minimum required surface profile is Ra 25 micron, corresponding to Rugotest No. 3, BN11a. Profile is obtained with a sharp angular abrasive.

Prior to application of HEMPADUR MULTI-STRENGTH all blasted surfaces must be cleaned from dust, abrasives, etc.

Concrete:

The concrete must be of a good quality and fully cured. Minimum pull-off value should normally be 20 kilopond/cm^2 measured after surface preparation.

Any cracks, crevices and voids must be repaired. The surface must be dry and free from dust, grease, etc. Laitance layer and loose particles must be removed, preferably by abrasive blasting.

The blasted or otherwise treated surface shall be cleaned from dust, abrasives, etc., preferably by high pressure fresh water hosing, whereupon complete drying must take place.

Seal the surface with HEMPADUR SEALER 0597. Necessary filling can then be done with e.g. HEMPADUR FILLER 3564.

APPLICATION EQUIPMENT: Spray application is carried out by "dual feed hot airless spray equipment", e.g. GRACO HYDRA-CAT SYSTEM No. 987241, DK. Other brands for the same purpose are available.

Dosing pump: Minimum ratio 1:45.

Proportion: 3 equal displacement cylinders, 2 for the BASE, 1 for the CURING AGENT.

Filters: 2 in-line filters on suction side.

Heating: 2 heating caps for preheating of material.

3 2100 W 220 V in-line heaters:
- 2 on BASE-line
- 1 on CURING AGENT-line.

Depending on conditions double capacity of heating may be necessary.

Hoses from proportion pump to mix manifold are heated, preferably with possibility of re-circulation.

Mixing aggregate: Static mixer 3/8". Min. 27 elements.

Automatic control of mixing ratio: Air Control Box reacting on pressure fall.

Hoses: Supply hoses: 3/8", preferably insulated or heated and with possibility of recirculation.

Spray hose: 1/4", 5 metres/16 ft., should be maximum.

Spray tip: Reversible type, orifice: 0.021-0.027".

PROCEDURE:

Heating: Heating of the material is necessary to reduce the viscosity. Optimum spray temperature is about 70°C/158°F. It is recommended to store the paint under warm conditions.

Prior to application, material is preheated to approx. 50°C/122°F e.g. by means of heating caps or by heating canons connected to the paint shed.

Flushing: Flush the system with HEMPEL'S TOOL CLEANER 9961. This is done to ensure complete cleanliness as well as to check proper functioning of the flush pump. Output pressure of this pump should be 120 bar/1740 psi.

Start:

Introduce the two components, BASE and CURING AGENT, into the equipment and empty of all foreign material.

NOTE: BASE and CURING AGENT of 3555 have different colours which, when mixed together, give the correct shade.

Circulate the materials until the (output) pressure of the three main dosing cylinders is identical - between 160 and 200 bar/2175-2900 psi. Then the material is ready for spraying.

If some or all the cylinders show too low pressure and no leaks are evident it may indicate that the viscosity of the material is too high. In this case, further heating is necessary.

Note that the output pressure of the two supply pumps always must be lower than that of the main pump cylinders. Recommended output pressure of supply pumps: 40 bar/580 psi.

Adjust heaters until correct temperature is achieved:

BASE : 70-80°C/158-176°F
CURING AGENT : 40-50°C/104-122°F

Before application the mixing ratio should be checked. Close the valve to the recirculation hoses. Measure the volumetric material flow of the two components separately at the outlets just after the dosing cylinders.

Spraying:

During the first seconds of spraying the paint will often "finger" due to cooling of the material(s) in the hose and gun.

NOTE: In order to minimize this problem keep spraying breaks and hose lengths at a minimum.

Furthermore, it is recommended to start by emptying spray gun, hose and static mixer of cold paint by spraying down into a bucket or drum.

Optimum distance between gun and steel surface is approx. 30 cm/1 ft. Distance may vary according to prevailing conditions and size/form of object.

Applied thickness must be inspected immediately after application with a wet film thickness gauge suitable for this range of thicknesses (0-1000 micron/0-40 mils). Additional material must be applied in case thickness is insufficient.

Control:

The automatic control panel will disconnect if the pressure falls during spraying (wrong mixing ratio).

NOTE: As an extra check of correct mixing ratios, evaluate whether the colour of the applied coat is right and homogeneous.

EQUIPMENT CLEANING: Proper equipment cleaning is essential for a successful operation.

Immediately after finishing the application the pump, hose and gun must be flushed with plenty of HEMPEL'S TOOL CLEANER 9961 until the cleaner itself is not contaminated.

NOTE: Pot-life of HEMPADUR MULTI-STRENGTH is only 3 minutes at the spraying temperature of 70°C/158°F after which the gelatination starts!

After all material has been removed from pump and hoses, the surge valve must be flushed and the suction pipes cleaned.

STRIPE COATING: Edges, corners, welding seams and places difficult to cover properly by spray should be stripe coated (touched up) either before or after the spray application.

For brush application HEMPADUR MULTI-STRENGTH 3555 and 3564 can be diluted with 10-15% THINNER 0808. Pot-life of diluted material is approx. 1 hour at 20°C/68°F. For preparation of smaller quantities take care to mix components in correct proportions. To obtain adequate film thickness on these areas apply an extra coat while the applied paint is still tacky.

The above is offered as a supplement to the equipment supplier's service manual which should be consulted.

DEVOE MARINE COATINGS

DEVRAN 288

DEVOE

PAINTS & COATINGS

DEVRAN® 288
HIGH TECHNOLOGY EPOXY COATING

FEATURES

- 100% Volume Solids Coating
- Solvent Free
- Provides a smooth, slick surface with low coefficient of friction to ice.
- Can be applied by conventional airless spray equipment.
- Tough, durable and excellent adhesion to blasted steel.

RECOMMENDED USES

Devran 288 is a high technology epoxy coating primarily designed for ice breakers

or

vessels cruising through ice conditions.

Devran 288 can be used to fill in pits in hull by spraying the material and using a squeegee to smooth the hull.

SPECIFICATION DATA

Coating Type	Amine - Epoxy
Color	Kit Number
Medium Gray	28812

Packaging—Available in 4-gallon kits.

Component Ratio	Base to Convertor
By Volume	3 : 1
By Weight	4.76 : 1

Pot Life	2 hours at 77°F (25°C)
Cleanup Solvent	#1 MD-1931 #31 MD-4438
Flash Point	212°F

Solids

By Volume	100%

Theoretical Spreading Rate

Sq. Ft./Gal. at 1.0 mil DFT	1,604
Density	13.4 Lbs. Per Gallon

Film Thickness

New Steel:
Two coats at 10 mils (250 microns) each coat minimum.

Old Steel:
Two coats at 13 mils (325 microns) each coat.

Dry to Recoat @ 75°F

Minimum	10 Hours
Maximum	48 Hours

SURFACE PREPARATION

All surfaces must be free of oil, grease and moisture before blasting to near white metal equivalent to Steel Structures Painting Council SP10-63T or Swedish Standard SA 2 1/2. The steel profile after blasting should be of a jagged nature as opposed to a peen pattern. Surfaces must be free of grit dust. Primer or first coat of the system should be applied to cleaned surfaces as soon as possible to prevent rerusting or contamination. For areas where sandblasting cannot be accomplished, hand clean, preferably with power disc sander, to bright, non-polished metal. Before applying first coat, be sure that all surfaces are free from comtamination.

MIXING AND THINNING

Devran 288 Coating is a two component product supplied in 4-gallon kits which contain the proper ratio of ingredients. The entire contents of each container must be mixed together. Power mix the base portion first to obtain a smooth, homogeneous condition. After mixing the base portion slowly for several minutes, add the convertor slowly with continued agitation. After the convertor add is complete, continue to mix slowly for 15 minutes. Thinning is not normally required or desired; however, at lower temperatures, small amounts (5% or less) of one of the solvents on the reverse page can be added. Any solvent addition should be made after the two components are thoroughly mixed. The pot life for the mixed material is 2 hours at 77°F (25°C). Higher temperatures will reduce working life of the coating, lower temperatures will increase it.

APPLICATION

Devran 288 Coating can be applied by both conventional air spray and airless spray equipment; however, airless spray is recommended. For air spray application, a fluid tip of .086" (DeVilbiss D tip) and an air cap with good break-up such as DeVilbiss #704 or 765 will give good results. Where airless equipment is used, a 30 to 1 pump and .023" to .031" tip size will provide a good spray pattern. Ideally, fluid hoses should not be less than 3/8" ID and not longer than 50' to obtain optimum results. For touch-up work, Devran 288 Coating may be applied by brush or roller. Care should be taken that all surfaces are clean and proper film thicknesses are obtained. A minimum of four days curing at temperatures above 60°F (15.6°C) should be allowed before the vessel is put into service. Longer curing times are required if temperatures are lower than 60°F.

PRECAUTIONS:

WARNING. Harmful if inhaled, could cause skin irritation and may cause respiratory reaction. Keep away from excessive heat and open flame. Use only with adequate ventilation. Applicators should be provided with suitable protective gear in accordance with the U. S. Department of Labor's Safety and Health Regulations for Ship Repairing. Do not use low flash point solvents to thin or clean up within enclosed areas.

DEVOE MARINE COATINGS CO.
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Rotterdam
Devoe Coatings b.v.
Zuidhoek 72A-3082 PM

CANADA
Dartmouth, Nova Scotia B3B 1N4
Devoe Marine Coatings of Canada, Ltd.
186 Joseph Zatzman Drive

APPENDIX III

ICCP LOG FROM
CANMAR KIGORIAK

) Box 890,
boken,
rsey 07030, U.S.A.
(01) 795-2044
12) 227-6657
0125919
WAZEDENS HOBOKEN N.J.

Wilson Walton International Limited
Pembroke House,
44, Wellesley Road,
Croydon,
CR9 2BU.
Tel (01) 686 7011
Telex 917168
Telegrams. CATHSHIP CRO.

Wilson Walton International A/S
P.O Box 72
1312 Slependen
Norway
Tel 544160
Telex: 16082
Cable: CATHSHIP OSLO

Materiaal Metingen B V
P.O. Box 63004,
Rotterdam 3006,
Holland
Tel 255748/255068
Telex: 24046
Cable: MATSHIP ROTTERDAM

Aquamatic system log

Vessel: V. CANMAR KIGORIAK
Voyage Number:
Date from: AUG 1/84
To: AUG 31/84
Month:

Vessel location	Aft System 1						Aft System 2 (if fitted)				Fwd System (if fitted)				[illegible]	Remarks
	Output		Potential (MV)				Output		Potential (MV)		Output		Potential (MV)			
	A	V	1	2	3	4	A	V	1	2	A	V	1	2		
AUGUST																
	112	11.8	151	139	118	129										
	113	12.3	149	157	104	127										
	115	12.1	148	134	110	130										
	072	9.1	150	137	120	142										
	085	10.1	151	129	105	116										AT ANCHOR
	144	16.3	157	122	065	111										
	120	12.3	158	141	104	131										
	095	10.1	149	140	107	127										
	082	9.4	153	151	123	141										
	144	18.0	155	137	075	113										
	132	13.5	145	124	098	112										
	132	13.7	156	146	121	147										
	051	7.0	130	137	139	153										
	145	14.2	159	154	099	137										
	132	13.5	151	116	034	080										
	115	11.4	145	152	121	141										OTHER SHIP ALONGSIDE
	161	18.7	151	121	075	113										
	154	17.7	151	122	069	116										
	152	16.6	150	137	073	118										
	118	14.4	148	136	091	126										
	154	15.6	161	137	071	118										
	149	17.0	145	127	075	117										
	156	17.3	163	141	088	119										
	164	20.8	153	127	065	110										
	15[illegible]	16.8	150	132	079	12[illegible]										
	170	17.	150	133	076	119										
	159	15.8	152	114	041	08[illegible]										[illegible] ICE
	139	16.6	152	128	073	118										
	168	21.0	171	082	04[illegible]	235										SUPPLY
	100	19.6	154	112	[illegible]	089										ALONGSIDE [illegible]
	134	19.4	149	122	[illegible]	111										

Officer in Charges Signature

Make out this form in triplicate - retain one copy on board, forward one copy to home office, one copy to Wilson, Walton International, Inc., P.O. Box M-890, Hoboken, New Jersey 07030
Record meter readings [illegible]

APPENDIX IV

THE EFFECT OF RELATIVE HUMIDITY ON COATING PERFORMANCE

Pages 274 and 275 from "Corrosion Prevention for Protective Coatings", C.G. Munger, NACA 1984, (reference 37) are copied with the kind permission of the National Association of Corrosion Engineers.

THE EFFECT OF RELATIVE HUMIDITY ON COATING PERFORMANCE

Throughout the text of this report statements of maximum ambient air relative humidity for proper coatings application have been given. Typically, the National Association of Corrosion Engineers in its publications recommends that no coating be done if the relative humidity is above 85%(50). The manufacturers of Inerta and Zebron specify a maximum of 80%, presumably because these high-performance coatings are more sensitive to moisture on the metal surface than are other commercial coatings.

The situation is not quite as simple as it appears. The concern with relative humidity involves the deposition of a thin film of moisture on the metal surface, which can result in:

1. A bloom of rust on cleaned metal if left uncoated for some time.

2. A physical barrier to paint adhesion.

For general guidance, two pages of, "Corrosion Prevention by Protective Coatings", C.G. Munger, National Association of Corrosion Engineers(37), are attached. In Table 10.8 shown in these sheets, temperatures of both metal and ambient air are shown to be critical. It is dangerous to assume that, because the ambient air has been heated so that its relative humidity is below 80% or 85%, no condensation of moisture will occur on metal being coated. Actually, it is preferable to heat the metal surface if feasible rather than to depend on heating air next to the metal.

Table 10.8 suggests that it may be very difficult to get ideal coating application conditions. In practice acceptable results can be achieved by using either of the 80% or 85% criteria, depending on the type of coating used. For high performance coatings the 80% value should be specified, and, if possible, even lower values should be achieved. Also, it is not necessarily sufficient to heat only the air around a ship's hull if the hull is significantly colder than the air.

In considering conditions inside enclosures used for painting ships hulls it is important to recognize that the method of heating the air (and the hull) has a marked effect on relative humidity:

1. If the air is heated indirectly as by electric heaters or other fuels fired into heat exchangers, the relative humidity decreases as temperature rises, even though the absolute humidity remains constant.

2. If the air is heated by direct firing of fossil fuels, water from the combustion enters the enclosure and increases the absolute humidity of the ambient air. The relative humidity will depend on the amount of fuel needed.

Copied from, "Corrosion Prevention by Protective Coatings", C.G. Munger, NACE 1984

" All coatings can be overcured to the point where their properties are diminished. In many cases, it is better to have a somewhat overcured condition than to have an undercured condition; *i.e.*, overcuring to a point just before the coating begins to break down. The coating will then have its maximum properties in terms of adhesion and resistance. In the case of the thermosetting coatings, however, undercuring leads to poor adhesion, poor water resistance, and poor resistance to solvents and chemicals Therefore, a somewhat overcured coating is preferable.

This is particularly true where coatings are to be used for immersion, for areas of heavy condensation, or where they are subject to constant chemical contact. Even some of the water-base organic coatings are improved by heat treatment. The original inorganic zinc coatings based on a high alkali silicate were cured by heat at around 350 to 400 F (180 to 205 C). The coatings reached their maximum resistance within approximately ½ hour and maintained these properties over a period of many years. Even now, while the heating process generally is not used for such coatings, if a rapid cure is required, heating of the water-base inorganic coating can substantially increase the speed of cure for quick handling and exposure.

Weather Conditions

Weather conditions can have a substantial effect on coating application. Weather conditions are less critical where coatings are applied to interior surfaces, although even in this case problems can occur. The ideal conditions for applying almost all coatings include a temperature of 70 F (21 C), little or no wind, and a humidity within 50 to 60%. All coatings respond well to such conditions. Moving away from the ideal, problems can occur which have a decided effect on the resistance of the coating.

Humidity

Humidity is one of the weather conditions which is an almost universal problem. This is because humidity may change rapidly, *e.g.*, from relatively low to very high during a single working day. It is the consensus of most coating authorities that coatings should be applied at temperatures no lower than 5 F (3 C) above the dewpoint. This may be difficult for the actual applicator to determine, since condensation is difficult to see. Wherever high humidities are encountered, particularly in coastal and marine areas, coating application must be carefully controlled as the temperature of the substrate approaches the dewpoint. Coatings applied over a surface covered with even a light film of condensation are almost always doomed to failure.

Table 10.8 shows the percent relative humidity above which moisture will condense on metal surfaces that are not insulated. This chart provides good guidelines as to when coating applications should be restricted. For example, if the metal temperature is 60 F (15 C) and the surrounding air temperature is 70 F (21 C) (which are reasonably normal conditions), there is a good chance of surface condensation if the humidity is 56% or above.

Table 10.9 shows how to determine the dewpoint if the air temperature and relative humidity are known. Both of these charts are helpful in assuring proper application conditions.

Hot, Dry Weather

Hot and dry weather conditions may or may not be good coating conditions. Under hot, dry conditions, overspray is much more of a problem, and coatings tend to dry much faster, often resulting in dry spray. For example, unless lacquer-type coatings are properly formulated for hot, dry conditions, excessive overspray can result when applied under such conditions. This is even more likely where there is even a mild wind condition. Dry spray also may result during the application of ethyl silicate-based inorganic coatings. Also, because these coatings require moisture to cure, they may not cure satisfactorily under such conditions. The solvents in epoxies may even dry so rapidly that the coating develops an uneven, orange peel-type surface. Moisture-cured polyurethanes also may not cure properly under such condi-

TABLE 10.8 — Percent Relative Humidity Above Which Moisture Will Condense on Metal Surfaces Not Insulated

Metal Surface Temp.	4 C 40 F	7 C 45 F	10 C 50 F	13 C 55 F	15 C 60 F	18 C 65 F	21 C 70 F	24 C 75 F	27 C 80 F	30 C 85 F	32 C 90 F	35 C 95 F	38 C 100 F	40 C 105 F	43 C 110 F	46 C 115 F	49 C 120 F
1 C(35 F)	60	33	11														
4 C(40 F)		69	39	20	8												
7 C(45 F)			69	45	27	14											
10 C(50 F)				71	49	32	20	11									
13 C(55 F)					73	53	38	26									
15 C(60 F)						75	56	41	17	9							
18 C(65 F)							78	59	30	21	14	9					
21 C(70 F)								79	45	34	25	18	13				
24 C(75 F)									61	48	37	29	22	16	13		
27 C(80 F)									80	64	50	40	32	25	20	15	
30 C(85 F)										81	66	53	43	35	29	22	16
32 C(90 F)											81	68	55	46	37	30	25
35 C(95 F)												82	69	58	49	40	32
38 C(100 F)													83	70	58	50	40
40 C(105 F)														84	70	61	50
43 C(110 F)															85	71	61
46 C(115 F)																85	72
49 C(120 F)																	86

% OF RELATIVE HUMIDITY

"

(SOURCE Ameron Co., Corrosion Control Principles and Methods, Section 7)

Copied from, "Corrosion Prevention by Protective Coatings", C.G. Munger, NACE 1984

"

TABLE 10.9 — Dewpoint Determination

Air Temp °C	Dewpoints (°C) at Various Relative Humidities							
	30%	40%	50%	60%	70%	80%	90%	100%
-1	—	—	—	—	-6.5	-4	-2	-1
4	—	-6.5	-4	-2	0.5	1.5	3.5	4.5
10	-6.5	-3.5	0.5	2	3.5	5.5	8.5	10
15.5	0	2	4	8	10	11.5	14	15.5
21	3	6.5	10	13	15	18	19.5	21
26.5	7	12	15.5	19	21	23.5	25	26.5
32	13	16.5	20.5	24	25.5	28.5	30.5	32
38	18	22	25.5	29	31	33.5	36	38

NOTE: It is essential to ensure that no condensation occurs on blasted steel or between coats during painting.

Air at a given temperature can only contain a certain (maximum) amount of water vapor. This proportion is lower at lower tempertures.

The dewpoint is the temperature of a given air-water vapor mixture at which condensation starts, since at that temperature its maximum water content (saturation) is reached.

In practice a safety margin must be kept, whereby the substrate temperature is at least 3 °C above dewpoint.

tions. In addition, water-base water emulsion coatings may dry so rapidly under these conditions that the coating does not properly coalesce, but may mud crack or craze, thereby resulting in an unsatisfactory coating.

Hot, Humid Weather

Hot, humid weather comprises another set of conditions to be considered. High humidity can create condensation problems, particularly as the late afternoon or evening approaches. This means that a constant check of the surface is necessary to make sure that coatings are not being applied over such condensation.

Warm, moist conditions are good for moisture-cured coatings such as ethyl silicate inorganics and polyurethanes. However, they are not as satisfactory for vinyls, since many solvents evaporate rapidly due to the temperature and, because of the rapid evaporation, the temperature of the coating may be reduced below the dewpoint so that progressive blushing can easily occur. This is also a problem with most lacquer-type coatings under humid conditions. *Blushing* is the condensation of moisture on the surface of the semiliquid coating, causing it to whiten. This blushing is caused by the precipitation of the coating resin on the surface due to the water, and it remains even after the coating is dry. A blushed coating is not satisfactory from either an appearance or resistance standpoint.

Cool, Dry Weather

Cold or cool, dry conditions [*i.e.*, above 40 F (5 C)] are usually good conditions for the application of lacquer-type or water-base coatings such as water-base inorganics, acrylics, or similar products. Under these conditions, the water dries from the coating relatively slowly, allowing the coating to make a good strong film. Silicate dispersion and lithium silicate-type inorganic zinc coatings are particularly good under such conditions. On the other hand, moisture cure inorganics may not cure for a long period of time under conditions which are cold and dry. This also may be true of moisture-cured urethanes.

Cold, Humid Weather

Cold, humid conditions are more satisfactory for moisture-cured coatings such as the ethyl silicate-base inorganics and moisture-cured polyurethanes. They are not as satisfactory for water-base coatings such as alkali-base inorganics or the water-base organics. It can be so cold and humid that the water will not evaporate from the coating over a period of many hours. Under such conditions, neither the water-base inorganics nor the organic water-base products will make a proper film on the surface. A poor coating with little resistance to corrosive conditions results. Epoxy coatings are particularly subject to poor curing during cold conditions. Increased humidity may be reactive with amine-type curing agents, causing further coating resistance problems.

Weather conditions are critical to the application of coatings. In fact, it often is necessary to select the type of coating that may be applied under the particular weather conditions which exist at the time.

Coating Coverage

Coating coverage can be defined in a number of ways. It can be the area which a gallon of coating will cover, the thickness of the film covering the surface, or the amount of coating required for a given area at a given thickness. Coverage, as it normally is described, is considered in an NACE Technical Committee Report entitled *Determination of Theoretical Coverage Rates of Inorganic and Organic Protective Coatings.*

> The "coverage rate" of a coating is defined as the area of a surface that can be covered at a uniform specified dry film thickness by a specified unit volume of a coating. In metric units, the coverage rate is expressed in sq. meters/liter at a dry film "

TABLE 10.8 - Percent Relative Humidity Above Which Moisture will Condense on Metal Surfaces Not Insulated

AIR TEMP ⟶ DRY BULB

↓ Metal Surface Temp.	4 C 40 F	7 C 45 F	10 C 50 F	13 C 55 F	15 C 60 F	18 C 65 F	21 C 70 F	24 C 75 F	27 C 80 F	30 C 85 F	32 C 90 F	35 C 95 F	38 C 100 F	40 C 105 F	43 C 110 F	46 C 115 F	49 C 120 F
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% OF RELATIVE HUMIDITY

Reproduced from: "CORROSION PREVENTION BY PROTECTIVE COATINGS"

TABLE 10.9 - Dewpoint Determination

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4	-	-6.5	-4	-2	0.5	1.4	3.5	4.5
10	-6.5	-3.5	0.5	2	3.5	5.5	8.5	10
15.5	0	2	4	8	10	11.5	14	15.5
21	3	6.5	10	13	15	18	19.5	21
26.5	7	12	15.5	19	21	23.5	25	26.5
32	13	16.5	20.5	24	25.5	28.5	30.5	32
38	18	22	25.5	29	31	33.5	36	38

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